RIGEX: PRELIMINARY DESIGN OF A RIGIDIZED INFLATABLE GET-AWAY-SPECIAL EXPERIMENT

THESIS

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THESIS

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Abstract

As space structures grow in size and complexity, their weight and cost increase significantly. The use of inflatable and rigidizable structures offers drastic improvements in all areas of spacecraft design. However, the Air Force and industry are hesitant to utilize unproven technologies in new designs. Therefore, the goal of this experiment is to verify and validate ground testing of inflation and rigidization methods for inflatable space structures in a zero-gravity space environment.

The Rigidized Inflatable Get-Away-Special Experiment is an autonomous, self-contained Space Shuttle experiment that will inflate and rigidize several structures. After inflation, the experiment will perform a structural analysis by exciting the rigidized structures and collecting vibration data. This thesis presents the preliminary design of the experiment and its major assemblies; including the structure, power, command and control, data handling, sensor, inflation, rigidization, and excitation systems.

A systems engineering approach is utilized to make design decisions based on a total system and life-cycle perspective. The systems engineering methodology focuses on defining objectives, requirements, and constraints; and then using an iterative process to develop a design that meets them.

RIGEX: PRELIMINARY DESIGN OF A RIGIDIZED INFLATABLE GET-AWAY-SPECIAL EXPERIMENT

I. Introduction

1.1 Background

The past 20 years have shown a dramatic increase in the use and exploitation of space. As space structures grow in size, the design complexity, weight, and cost of the structures also increase. With recent budget declines and goals of better, faster, and cheaper systems; designers are forced to develop structures that are more efficient than traditional mechanically deployed structures. One potential solution is the use of inflatable, rigidizable structures for permanent space structures.

This United States Air Force is also investigating inflatable structures. The Space Vehicles Directorate of the Air Force Research Laboratory (AFRL/SV) has recognized the value of inflatable structures in large space structures (11). They highlight the three factors that drive spacecraft design: aperture size, available power and launch cost. Inflatable and rigidized structure have the potential of drastically impacting all three of these factors.

According to AFRL, "very large, deployable structures ... will make almost any aperture size possible and inexpensive ... (and) extremely lightweight deployable structures will enable large power farms on orbit to provide previously unheard of amounts of spacecraft power (11)." Additionally, by reducing packing size and weight, launch costs can be reduced significantly. With the current fiscal constraints placed on current and future space systems, the Air Force is working to find better and cheaper methods of achieving space superiority. Inflatable and rigidizable structures offer one method of achieving that goal.

Inflatable technology has made great strides from research, development, and orbital testing. Several current spacecraft designs incorporate inflatable structures and their benefits of lower weight, cost, and packing volume. However, significantly less research and development has been done with rigidizable structures. Most current work on rigidizable structures has been ground-based laboratory experiments or analytical simulations.

Actual hardware testing in a space environment has been limited. The three relevant conditions of the space environment which influence inflation and rigidization are reduced pressure, temperature, and gravity. Although the vacuum and temperature profiles of space can be duplicated in thermal-vacuum chambers, the zero-gravity environment can only be duplicated for short time periods in specialized aircraft, and no current system can test all three simultaneously.

1.2 Scope of Project

The ultimate objective of this project is to enable the application of large-scale inflated and rigidized structures to operational space systems. However, the aerospace industry is reluctant to accept operational use of inflatable and rigidized structures until more data on space-rigidized structures is available. In addition to the data collected in orbit, it would be beneficial to test space-rigidized structures in a controlled laboratory environment.

In order to meet this objective, designers and operators must be confident in the reliability and quality of these large space structures. Although space testing of these structures would be ideal, ground testing is much more cost and time effective. Therefore, in order to validate ground testing, a comparison of ground and space test data is necessary. By comparing the inflation, rigidization, and modal analysis of similar structures in both settings, the ground test methods can be validated and applied to larger and more complex systems.

The goal of this thesis effort is to design a system that will collect data on space rigidized structures. By operating the system in space and in a ground laboratory, the data can be analyzed and compared. Once orbital data is compared to ground data, the ground tests procedures can be verified as accurate and more complex systems can be developed without full scale testing is space.

The Rigidized Inflatable GAS Experiment (RIGEX) project is a Get-Away-Special (GAS) experiment. The GAS experiments are self-contained canisters that are mounted inside the Space Shuttle cargo bay. The RIGEX project will provide on-orbit data on the controlled inflation, rigidization, and structural analysis of several structures. Once all data is collected, the entire experiment will return to Earth where further laboratory testing and analysis can be performed. This thesis outlines the preliminary design of the experiment, the design alternatives and decisions, and the systems engineering processes followed to achieve the design.

1.3 Systems Engineering Process

1.3.1 Overview. Prior to implementing a systems engineering process (SEP), it is necessary to define systems engineering. This proves difficult, since there is no single agreed upon definition. This does not imply that systems engineering is vague; rather, its broad application across many disciplines results in definitions which emphasis different aspects of systems engineering.

First, a system can be defined as "a set or arrangement of elements (people, products, and processes) that are related and whose behavior satisfies customer/operational needs and provides for the life cycle sustainment of the products (12)." Note that the system is not only the final product, but includes the people, processes, and additional resources required for *lifetime* sustainment.

Using the above definition of a system, the following are several ways of defining systems engineering:

> "... an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and life-cycle balanced set of system people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts ...; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making." (*NASA System Engineering Handbook (19)*)

> "... the discipline of managing the development of complex systems. It focuses on defining the required functionality early in the development cycle, documenting these requirements, then proceeding with the design synthesis ... (which) integrates all disciplines and specialty groups under one umbrella, employing a structured design process ... (that) considers both the business and technical needs of all customers." (*International Council on Systems Engineering (14)*)

Both definitions emphasis the multi-disciplinary and customer aspects involved in developing a project. Next, to implement a systems engineering into the design of this project, a systems engineering approach must be chosen. Generally, a SEP should be applied if any of the following are true of the project or its components (14):

- it is complex
- the components are not available off-the-shelf
- it requires special materials, services, techniques, or equipment for development, production, deployment, test, training, support, or disposal
- it cannot be designed entirely with one engineering discipline

From the attributes listed above, it is clear that RIGEX experiment would benefit from a systems engineering approach. To facilitate the design, component selection, testing, construction, and operation of RIGEX, an iterative SEP was needed. In reviewing system engineering methodologies and standards, several processes were considered to determine which best fit the size, scope, and complexity of this project.

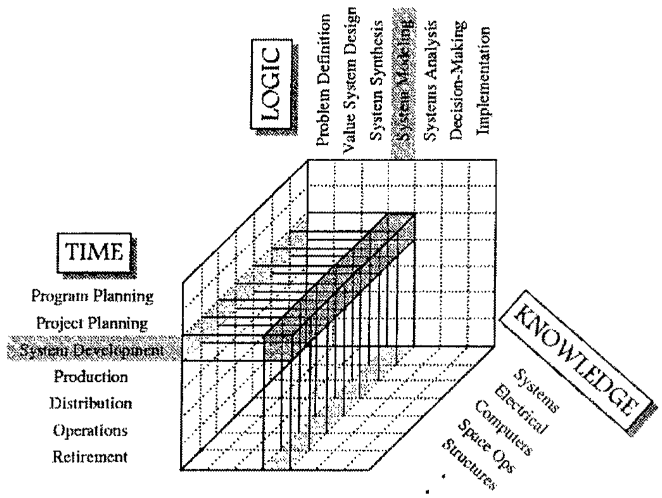

Figure 1.1 Hall's Morphological Box for Systems Engineering (10)

Each of these processes is outlined and then one is selected as the model for this project.

1.3.2 Hall. Although the concept of systems engineering has existed since the 1940s, one of the first widely accepted systems engineering process was developed by Arthur D. Hall in 1969 (10). Hall's process outlined a three-dimensional box, shown in Figure 1.1, which categorized the three fundamental dimensions to systems engineering: time, logic/procedure, and knowledge. The time dimension relates to the phases of a systems development, from initial planning to system retirement. The facts or knowledge dimension is a scale of professional disciplines that are necessary for the system, ranging from engineering to business, law, and arts. The third dimension, logic, provides the SEP for problem solving and system development. The iterative, seven-step systems engineering process used by Hall is: problem definition, value system design, system synthesis, system modeling, system analysis, decision making, and implementation.

Table 1.1 NASA Systems Engineering Process

Step	Description
1.	Recognize Need/Opportunity
2.	Identify and Quantify Goals
3.	Create Alternative Design Concepts
4.	Do Trade Studies
5.	Select Concept
6.	Increase the Resolution of the Design
7.	Perform the Mission

1.3.3 NASA. The National Aeronautics and Space Administration (NASA) Systems Engineering Handbook (19) was written to provide all NASA personnel with a description of systems engineering as it should be applied to the development of large NASA projects. Although it is not intended as an absolute template for all projects, it does discuss generic descriptions of processes, tools, techniques, and pitfalls.

The NASA approach attempts to "see that a system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk (19)." The cost-effective focus is obviously a major consideration in their process. Their process also focuses on the iterative nature of systems engineering, called *The Doctrine of Successive Refinement* (19). The SEP used by NASA is outlined in Table 1.1.

1.3.4 IEEE. The Institute of Electrical and Electronics Engineers (IEEE) has formalized and published a standard titled "IEEE Standard for Application and Management of the Systems Engineering Process (12)." This standard is comprehensive and covers most aspects outlined in the other processes. It also "focuses on the engineering activities necessary to guide product development while ensuring that the product is properly designed to make it affordable to produce, own, op-

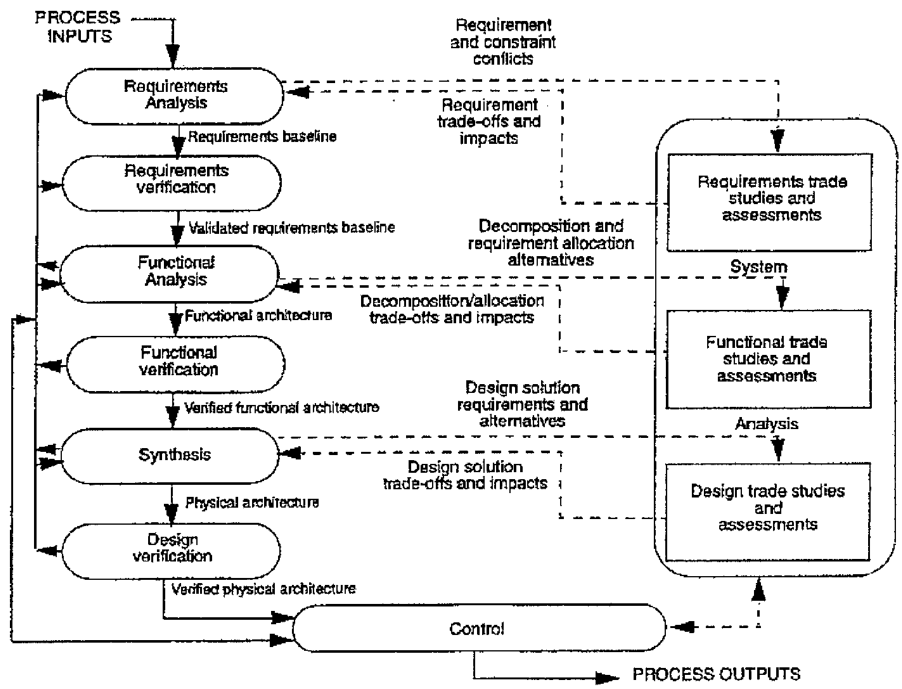

Figure 1.2 IEEE System Engineering Process (12)

erate, maintain, and eventually to dispose of, without undue risk to health or the environment (12)."

In the IEEE SEP is shown in Figure 1.2, where the left side lists the process inputs and shows the steps to be followed. The dashed arrows outline the interactions between the process outputs (or products) and the inputs. An interesting element to the IEEE process is the inclusion of human elements and processes that are often forgotten in defining the system. These processes include development and test, manufacturing, distribution and support, operations and training, and disposal.

1.3.5 SMAD. The Space Mission Analysis and Design (SMAD) process is tailored to the design and development of space systems and offers a step-by-step iterative process to follow (27). Table 1.2 outlines the four phases and eleven steps involved in the SMAD process. For an in-depth description of each step, see the SMAD text.

Table 1.2 Space Mission Analysis and Design (SMAD) Process

Step	Define Objectives
1.	Define Broad Objectives and Constraints
2.	Estimate Quantitative Mission Needs and Requirements
	Characterize the Mission
3.	Define Alternative Mission Concepts
4.	Define Alternative Mission Architectures
5.	Identify System Drivers for each
6.	Characterize Mission Concepts and Architectures
	Evaluate the Mission
7.	Identify Critical Requirements
8.	Evaluate Mission Utility
9.	Define Mission Concept (Baseline)
	Define Requirements
10.	Define System Requirements
11.	Allocate requirements to System Elements

1.3.6 SEP Selection. Although Hall's process provides a good framework for developing this project, several aspects of his process do not fit this design. For example, step 2 (value system design) provides for a mathematical calculation of utility for each alternative design. This utility is based upon the user's preference for traits of the final system. In this project, the user is not as concerned with how the experiment is performed, as long as the data is collected in a valid, accurate manner.

The intent of the IEEE standard is to produce one methodology that all areas of business and industry can apply. For that reason, it is very broad and detailed in many areas. To be applicable for this project, the process would require substantial tailoring; therefore, it is probably not the best choice for this project.

The SMAD process provides a good framework for developing a system to meet a user's need. However, in this project the user has already defined many aspects of the design; such as the use of a GAS experiment, and several specifics on the inflatable structures. The SMAD process would require tailoring at many steps, and the process could not be performed in it's entirety.

The NASA SEP provides the best framework for this type of project. The phases of NASA life-cycle of a system include the operation, budgeting, and scientific studies required to develop the system. These complexities are all necessary when designing a large system to meet a new need/opportunity; however, this project has a much more limited scope. Therefore, the steps will be tailored and to enable each step of the process to be applied. Step one, recognize need or opportunity, is completed in that the user has determined the need for data on space rigidized structures. The next step is to identify and quantify the goals of the project. This is accomplished by defining four aspects of the project: the mission statement, objectives, requirements, and constraints. Without a clear definition of these items, the final design may not meet the sponsor's expectations.

1.4 Mission Statement

The experiment is interested in the inflation and rigidization characteristics and the dynamic properties of the rigidized structures. The orbital data from the experiment will be compared to those conducted in the laboratory. The comparison of the data will be used to validate ground testing and to design future rigidizable space structures. After discussions with the user, the following mission statement was developed and approved:

To verify and validate ground testing of inflation and rigidization methods for inflatable space structures against a zero-gravity space environment.

1.5 Objectives

Once the mission statement is approved, the next aspect to define is the broad objectives. Although there are typically multiple objectives for space systems, the primary objective is the overriding reason the system is being developed. The secondary objectives can be additional technical objectives or political, social, and educational objectives (27).

The mission statement and objectives are purposefully nontechnical and qualitative to prevent a specific solution to the problem. This also allows the design to mature and explore options the user may not have considered, to best meet the mission statement within the requirements and constraints. Once determined, the mission statement and objectives should not change throughout the development of the systems. Given the above mission statement, the following primary and secondary objectives were developed for this project and approved.

Primary Objective:

– *Design a GAS experiment to collect data on space rigidized structures for validation of ground testing methods.*

Secondary Objectives:

– *Return inflated/rigidized structures to laboratory for additional testing.*

– *Enable application of rigidized structures to operational space systems.*

– *Implement systems engineering principles into the experiment's design.*

Usually, the objectives would not specify the method of experiment being conducted (i.e. Get-Away-Special). However, part of the validation of ground testing includes post-flight testing of the inflated and rigidized structure. Since there are limited methods for returning space experiments to Earth, the user decided upon a GAS experiment. Additionally, the user has secured a flight reservation for a GAS experiment aboard the Space Shuttle.

1.6 Requirements

The third aspect is the definition of the quantitative goals of the project, also called requirements. The requirements are based on performance needs, applicable technology, and constraints. However, the requirements are flexible (unlike the objectives) and often change throughout the system's development.

There are several ways of communicating objectives. One method is by defining the threshold and target values for each requirement. The threshold is the minimum

Table 1.3 RIGEX SE Requirements

Operational	Requirements
Inflation	Multiple storage & deployment configurations
Rigidization	Prefer multiple rigidization methods
Test Data	Deployment position, structural response, post-flight analysis

Functional	Requirements
System Design	Maximize use of off-the-shelf, flight-tested equipment
Duration	Storage for at least 4 months at launch site
	On-orbit for maximum of 14 days
Availability	One time mission and operation (high reliability)
Survivability	Shuttle launch and re-entry
Power	Provided internally
Command & Control	3 user inputs, otherwise autonomous
Data Collection	Stored internally for post-flight analysis

acceptable value and the target is the true desired value. This method provides the designers much more information; however, it requires detailed knowledge of available technology and the system being developed.

Another method, and the one used for this system, is defining the threshold values or the preferred direction of improvement for each requirement. This method requires less specific knowledge of the system and is often used in the preliminary design. Table 1.3 outlines the requirements for the RIGEX system.

1.7 Constraints

Trades between requirements and constraints are common in the system engineering process, because usually all of the users requirements cannot be realistically met by one system. From a project management perspective, these trades occur between three project measurements: cost, schedule and performance. For example, performance is often traded to reduce the cost of a system. From a systems engineering perspective, trades occur among allocation of resources between different subsystems or disciplines. Ultimately, it is the system engineer's task to find the best balance between requirements and constraints.

Table 1.4 RIGEX SE Constraints

Constraint	Limit	Imposed by:
Weight	200 lbs	NASA
Size	19.75 inches (diameter)	NASA
	28.25 inches (height)	NASA
Life Cycle Cost	$200,000	User
Development Time	2 years	User
Flight Time	14 days	NASA

Since this project is a GAS experiment, most of the constraints are imposed by NASA regulations. Additional constraints on cost and schedule are imposed by the user. Table 1.4 outlines the constraints on the RIGEX system.

1.8 System Architecture

Although, at this point, no design work has begun on the project, a preliminary system architecture can be developed. The system architecture provides a breakdown of the complex system into smaller, more manageable pieces. Often the first level in the system architecture is a breakdown of the major subsystems of the final product. Again, there is more to a final system than the physical hardware. The development and operational processes need to be considered from the beginning, and therefore should be included in the system architecture.

As a system is developed, the system architecture should evolve and grow. Initially, the architecture provides the overview and work breakdown structure necessary to develop complex projects. When the project develops more detail and direction, the architecture must be continually updated and amended. The systems engineering process should be applied at each level of the architecture, until a single design discipline can perform the specialized task independently. This ensures that each subsystem is optimized to perform its function within the system and all the interactions between the subsystems are understood and accommodated. How-

ever, since this project involves a smaller scope and time frame than large/complex systems, the system architecture is limited to two levels.

The initial system architecture for this project is shown in Figure 1.3. The top-level items represent the anticipated subsystems involved in the experiment, as well as the processes necessary to complete the project. The second level items describe the primary decisions that are required in designing and integrating the subsystems.

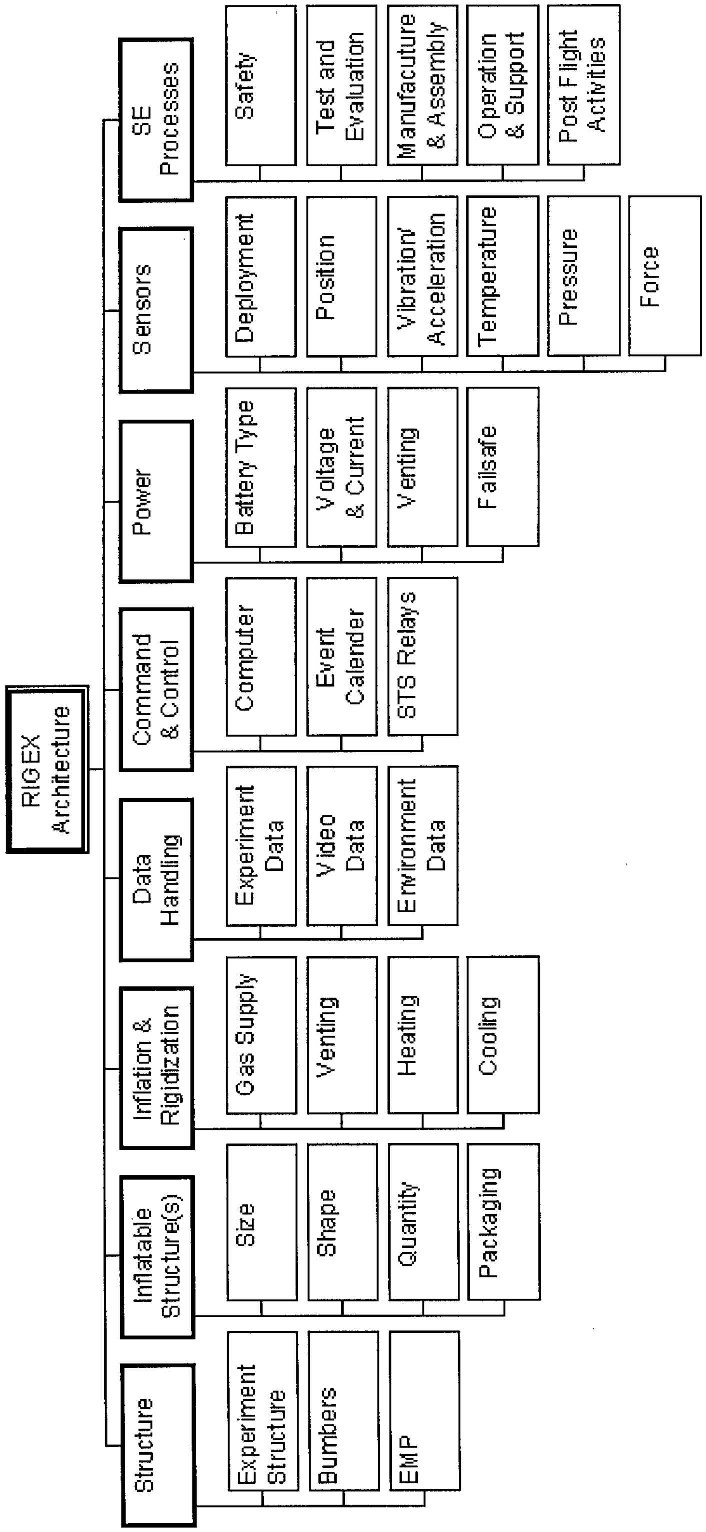

Figure 1.3 RIGEX System Architecture

II. Literature Review

2.1 Inflatable Structures

2.1.1 Overview. The use of inflatable structures dates back to the beginning of the United States space program in the 1950s. Since then a steady, although limited, interest in the development and application of inflatable structures for space structures has continued. An inflatable structure can be defined as any form which expands to a predefined shape by increasing the air pressure within the structure. This is usually done by introducing gas into the structure. Due to the vacuum of space, the pressure required to maintain inflation is very low, on the order of 10^{-4} atmospheres (atm).

Most purely inflatable structures require make-up gas to maintain pressure within the structure. This is especially true for systems that are expected to have an on-orbit lifetime of five to ten years. These structures usually carry relatively low loads and therefore require a low inflation pressure. For structures that are intended to carry a high load, there are two choices. Either use a much higher pressure within the structure, which will last only a short time, or rigidize the structure after inflation. The second method, rigidization, shows the most promise for future applications.

The primary advantages of inflatable structures, compared to mechanical structures, are: weight and packaging, strength, production cost, reliability, engineering complexity, and the ability to form complex shapes, as well as favorable thermal and dynamic characteristics. Each of these advantages is described below.

The decreasing budgets and increasing cost of space launches has forced industry to examine cheaper ways of lifting systems into orbit. Due to their low weight and efficient packaging, inflatable structures are ideal for saving both weight and volume. Inflatable systems offer up to a 50-percent weight reduction over the best mechanical systems and up to a 25-percent volume savings (3). As launch vehicles

Table 2.1 Typical Data on Current Launch Systems

Launch System	Maximum LEO (kg)	Payload GEO (kg)	Payload Diameter (m)	Fairing Length (m)	Cost to LEO FY00 (dollars/kg)
Atlas II	8640	1050	4.2	12.0	11.6-12.7
Delta II	5089	3890	2.9	8.5	9.8-10.8
STS	24400	n/a	4.5	18.0	16.4
Titan IV	21645	18600	4.5	18.9	9.9
Ariane 5 (ESA)	18000	12000	4.5	12.0	7.2
H-2 (Japan)	10500	6600	4.6	5.0	15.2-19.5
Long March (China)	13600	2250	3.8	6.0	5.5
Proton (Russia)	20900	2500	4.1	15.6/7.5	2.6-3.6

became bigger and better, the limiting constraint on payloads became the internal diameter of payload fairing. Even heavy lifters, such as the Titan IV, have an upper limit on how large payloads can be. Even if a payload can be designed and packed inside these larger fairing, the cost per pound to launch the system is enormous.

Table 2.1 summarizes several payload parameters of current launch systems. This table is a compilation of data in the SMAD text (27). Due to the multiple configurations of each vehicle, the maximum values are listed for each launch system. For this table, low Earth orbit (LEO) altitude is considered 185 kilometers and the costs are per kilogram to LEO. From this information, each kilogram or cubic meter saved by the implementation of inflatable structures reduce the launch cost significantly.

With regard to strength, inflatable structures offer several advantages to mechanical systems. Conventional mechanical systems require many joints and hinges to fold into the launch configuration. For example, a 100-meter boom deployed from the Space Shuttle would require at least six connected sections, whereas an inflatable boom could be rolled or folded for a continuous shape once deployed. In mechanical systems the loads are concentrated on the joints, which must be reinforced (making them heavier and more complex). In inflatable systems the loads are distributed over the entire boom, therefore making them potentially stronger. Where mechanical systems draw their strength from material properties, inflatable systems use the inflation pressure and/or rigidization to achieve desired strengths.

Inflatable structures are also much easier to manufacture. As technology is developed and proven, the same techniques can be easily repeated to produce larger and more complex systems. An inflatable system is essentially made up of flat material assembled with seams, a package to hold the material, and an inflation system. Complex shapes are also much easier to design and build using inflatables. The material is simply cut and assembled such that at equilibrium pressure the desired shape is achieved. Dr. Costa Cassapakis has estimated that "... the engineering of new systems is perhaps 50-percent cheaper than for other deployables (3)."

For reasons above (weight, complexity and manufacturing), inflatables have lower production costs that comparable mechanical systems. Although specialized tools may be required, overall production costs can be one-tenth that of large complicated systems (3).

The deployment of inflatable structures is also dependable. The simple design of inflatable structures allow for a predictable and reliable inflation and deployment. The primary failure point is the initiation of the gas release for inflation, however, sound engineering principles have minimized this risk. Over the past 20 years, deployments of inflatable structures have caused few problems. Even when inflation and deployment do not go as expected, often the desired configuration is still achieved, as with the Inflatable Antenna Experiment (8). This is due largely to the nature of inflatables; as pressure increases inside the structure, any kinks or hang-ups are corrected.

Finally, inflatable structures offer favorable dynamics and thermal responses. Inflatable systems resist distortion due to the constant inflation pressure, which reduces the vibration and frequencies of motion. If the system in rigidized after inflation, it still resists vibration because of the material properties. Similarly, the materials used in inflatables possess desirable thermal properties. The large, continuous surface of inflatables allow uniform heat transfer, which minimize distortions due to thermal expansion.

Overall, inflatable structures offer many advantages to the space community. The focus on more efficient designs is forcing designers to find new ways of reducing payload size and weight and increasing operational reliability. Also, recent advances in composites are making inflatables better and stronger. Whether inflatable structures are the primary system of a spacecraft or just a subsystem, they will allow designers to do more with less.

2.1.2 History. Over the past 50 years, many organizations have used inflatable structures for a variety of applications. One of the pioneers in the use of inflatable structures was the Goodyear Corporation. Starting in the late 1950s, they began to investigate the use of inflatable structures for radar applications. They developed a radar calibration sphere which was made from many large hexagonal panels bonded together to form a sphere. The final structure was approximately 6 feet in diameter. Also developed was a "lenticular inflatable parabolic reflector," which was an inflatable rim of about 12 meters in diameter and two parabolic surfaces.

The first major space project involving inflatable structures was Echo 1. Echo 1 began as a NASA project in 1958 with the objective of providing passive, space-based communications reflectors. It was made of extremely thin mylar sheets coated with vapor deposited aluminum and bonded together. The 100-foot diameter sphere used sublimating powders for inflation. Following numerous ground, vacuum, and high altitude tests, Echo 1 was launched to a 1000-mile orbit aboard a Delta rocket on August 12, 1960. The final sphere weighed 136 pounds and fit in a 26-inch diameter spherical container. Echo 1 remained on orbit and provided an adequate reflective structure for several months, proving that inflatable structures were viable. After Echo 1, NASA developed and launched a larger version (Echo 2), with a 135-foot diameter; as well as a smaller series called Explorer (7).

Following the successful launch and orbit of these inflatable systems, the space community shifted its focus to more traditional mechanically deployed systems. The

probable reason for this shift, even though inflatables had shown great promise in packing efficiency and large volume, is that industry was much more familiar and comfortable with mechanical systems. The risks of mechanical systems were better defined and perceived as less than inflatables. At that time there were concerns regarding long-term material properties in space, as well as the potential for meteoroid impacts which could deflate the systems.

Additionally, in the time frame of the 1970s and 1980s, larger and more powerful launch systems were being developed and implemented. This removed the strict need for lighter and more compact launch configurations; which are the two primary advantages of inflatable structures. In the race for dominance in space, designers opted for familiar and reliable systems over "cutting-edge" inflatables.

However, research and development of inflatables did not stop. Many individuals and organizations recognized the potential applications of inflatable structures and continued to make progress in the field. Through the 1980s and early 1990s, both ground and orbital tests were conducted to validate the use of inflatable structures. Organizations currently working in the inflatable structures field include L'Garde, Contraves, SRS, Aerospace Recovery Systems, ILC Dover, Thiokol, and Jet Propulsion Laboratory (JPL).

2.1.3 Current Projects. During the fiscal constraints of the 1990s, industry focus again shifted to how things could be done "better, faster, and cheaper." Proponents of inflatable structures were ready to prove the advantages of their systems. This section summarizes the goals and accomplishments of several inflatable structure projects over the past ten years.

2.1.3.1 Inflatable Antenna Experiment. The Inflatable Antenna Experiment (IAE) was developed by L'Garde to meet the NASA goal of verification and/or validation of innovative space technologies. The objectives of the experiment were to validate the deployment of a 14-meter inflatable parabolic reflector,

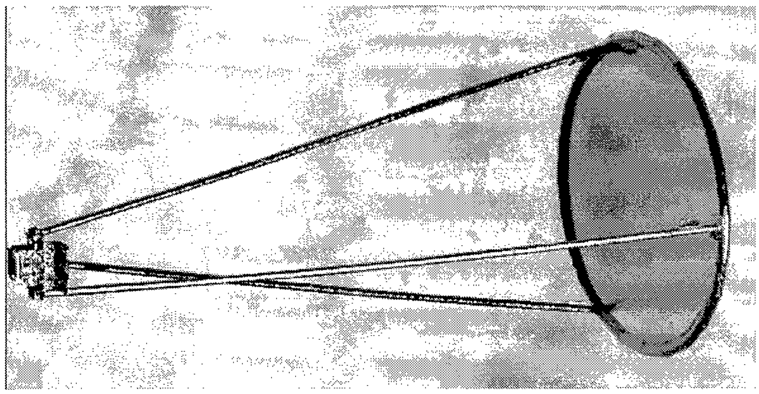

Figure 2.1 Inflatable Antenna Experiment

measure the surface accuracy of the reflector, investigate structural damping under operational conditions, and demonstrate that a large flight quality structure could be built at low cost and stowed in a small container (6). The system can be broken down into five main components: the Spartan spacecraft, structure, reflector, canister, and instrumentation. The final configuration can be seen in Figure 2.1.

This NASA Spartan spacecraft was used as a platform for the experiment and provided basic subsystem functions. The system was carried into orbit aboard the Space Shuttle. Once in orbit, the Spartan spacecraft provided power, attitude control, and data recording functions.

The structure of the IAE was provided by three 92-foot length, 18-inch diameter inflatable struts extending from the canister. These struts are connected to the 50-foot diameter inflated torus. Once the struts and torus were inflated, the reflector was inflated. The torus provided rim support for the reflector, which kept the reflector from inflating into a sphere. All inflated sections of the experiment maintained pressure and strength through the inflation gas of the experiment.

The reflector had two components, the reflector and the canopy. The reflector is aluminized mylar and forms a parabola which focuses on the Spartan spacecraft. The canopy is essentially a clear mylar parabola. The two components are connected and sealed at their edges.

The canister provided the interface between the structure and the Spartan spacecraft. Once the experiment was activated, the deployable doors of the canister opened to begin the inflation procedure. The inflation system was also contained within the canister. The instrumentation was the final element of the IAE. It consisted of a surface measurement system to evaluate the accuracy of the inflated reflector. Video cameras were also used to record the inflation and deployment of the system.

The IAE was carried into orbit by STS-77 in 1996. Once the experiment was placed into a free-floating orbit by the Space Shuttle crew, the inflation process began. After some unexpected dynamics (rotation and pitch), the final configuration was achieved. The experiment collected data for one orbit (90 minutes). After all tests were performed, the experiment was jettisoned and the Spartan spacecraft (and data) were retrieved by the Space Shuttle. By all accounts the IAE was a success and has generated significant interest in the use of inflatable systems (8).

2.1.3.2 Inflatable Sunshield in Space. The Inflatable Sunshield in Space (ISIS) program is being conducted by ILC Dover in conjunction with JPL as part of the Next Generation Space Telescope (NGST) program. The NGST program is a space telescope that will examine stars, galaxies, and the universe. In order to achieve the goals of NGST, the telescope must be protected from direct sunlight and heating. An approximately 15-meter by 33-meter diamond shaped sunshield will provide passive cooling and a light shield for the spacecraft (5). See Figure 2.2 for a conceptual drawing of NGST and a scale model of the sunshield.

The ISIS program is tasked with the development of a large, low-mass, high-packing efficiency sunshield. The goals of the project are to demonstrate a controlled deployment, rigidization, and dynamic response. To achieve these goals, the project will deploy a one-third scale (15 by 34 foot) inflated and rigidized sunshield from the payload bay of the Space Shuttle.

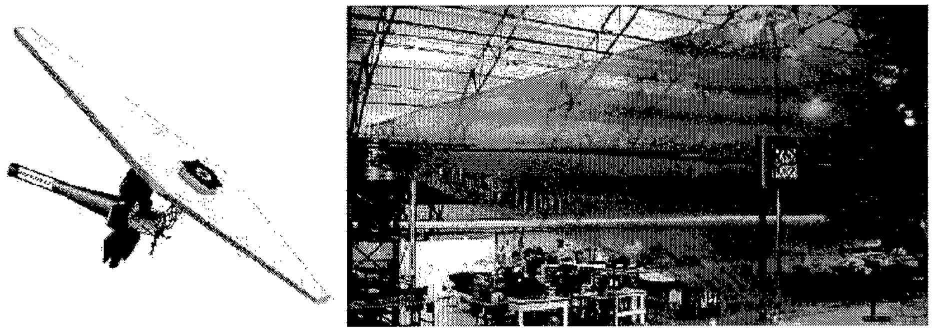

Figure 2.2   NGST Conceptual Model and ISIS Scale Model

The ISIS deployment is intended to occur in three phases. First, the experiment is extended out of the payload bay. The booms will be heated to +120°C until curing begins. Next, the pressure in the booms in raised to 3.5 psi and maintained while the booms are deployed laterally and then longitudinally at a rate of two feet per minute. Finally, the booms are allowed to cool and the pressure is vented inside the booms. The Space Shuttle will then apply appropriate loading and measure the response. If successful, the ISIS program should provide valuable information on rigidizable space structures.

2.1.3.3 ARISE. The Advanced Radio Interferometry between Space and Earth (ARISE) is a concept that uses large orbiting antennas (20 to 30 meter diameter) in conjunction with ground antennas to synthesis a highly sensitive RF interferometer. Figure 2.3 shows a conceptual drawing of one orbiting antenna, where the support beams and circular truss are inflatable structures. Although still in the conceptual phase, the use of inflatable technology makes this a very feasible project.

Originally designed as a mechanically deployed reflector, ARISE was expected to cost hundreds of millions of dollars, weigh several hundred kilograms, and require heavy lift capability to place the structure in orbit. Additionally, the large mass and inertia of the spacecraft would drive the attitude control and lifetime of the system. By employing inflatable technology, the cost, weight, and size are expected to be reduced to 20-30 million dollars, 100 kilograms, and 1 cubic meter respectively (26).

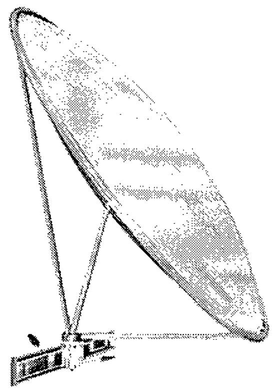

Figure 2.3 ARISE Inflatable Spacecraft

ARISE is an excellent example of how inflatables can drastically reduce multiple aspects of a spacecraft, which may have otherwise been impractical. As inflatable technology progresses, more data on deployment, rigidization, structural loading, and reliability will further enhance the usefulness of inflatable structures.

2.1.3.4 Inflatable Rigidizable Truss Structure. Another project L'Garde Inc. is pursuing is the use of inflatable tubes to produce triangular truss structures. This project has taken the next step of integrating complex joints into inflatable structures. Figure 2.4 shows the prototype truss.

The truss uses water-impregnated composite tubes connected by cast aluminum joints. The purpose of the program is to test packaging, thermal cycling, vibration, deployment, rigidization, bending/compression loads, and natural frequencies of the structure. Testing will be performed in ambient and vacuum environments. The results and lessons learned from this program will provide valuable data on rigidization and the effects of joints of loads and vibration in complicated rigidized space structures (9).

2.1.4 Potential Uses. Inflatable and/or rigidizable structures offer many advantages for future space application, as discussed earlier. Efficient, reliable, and

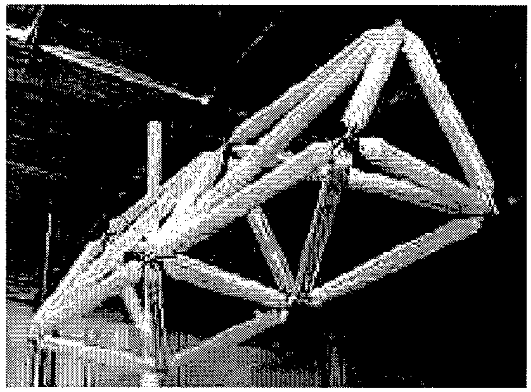

Figure 2.4 L'Garde Inflatable Space Truss

strong structures are required to construct and fly "large" space systems. Inflatable structures are envisioned to be used for the following applications:

- booms
- solar array support structures
- sun shade support structures
- planar-array antennas
- solar concentrators
- reflector antennas

As space structures grow is size, there is an increasing need for large booms and trusses with desirable properties: high loading, low vibration, and low bending. As the structures get larger, the cost of mechanically deployed systems increases dramatically. As inflatable/rigidizable structures are tested and validated for strength, lifetime, and availability; they will increasingly outperform mechanical systems in cost, weight, and launch size.

With regard to support structures, the use of inflatable systems can also lower the weight and size of the solar array and sun shades. This enables more weight and area for the actual payload of the spacecraft. As with booms, solar arrays are increasing in size to provide the necessary power for spacecraft. By implementing

inflatable structures, the solar arrays can become larger, without sacrificing payload weight or size. Sun-shields are used to regulate the thermal environment of the spacecraft, as demonstrated with inflatable structures in the ISIS program.

2.2 NASA Get Away Special Experiments

2.2.1 Overview. In the 1970s, while NASA was designing and building the Space Shuttle, there was a desire to foster interest and expand access to space. The Shuttle Small Payloads Project Office (SSPP) was given the responsibility to provide very low cost access to space to many potential users. Although each shuttle mission involves single or multiple primary/secondary payloads, there is often excess space and weight available for smaller payloads.

To utilize this space, SSPP developed several programs to enable individuals to place small self-contained payloads into the shuttle's cargo bay on a space available basis. These programs are known as Space Experiments Module, Hitchhiker and Hitchhiker Junior, and Get Away Special Canister (GAS Can).

The GAS program provides limited mechanical and electrical interfaces between the shuttle and the self-contained experiment. All GAS experiments are expected to focus on research and development (R&D) and are not used for direct commercial use. The goals of the GAS program are:

- Encourage the use of space by all researchers
- Foster enthusiasm in younger generations
- Increase knowledge of space
- Be alert to possible growth in a prime experiment
- Generate new activities unique to space

Once GAS experiments are "ready-for-launch", NASA assigns a flight category and possible launch schedule. The flight categories are currently educational, commercial/foreign, and U.S. government; where the categories are put into a rotation

Table 2.2 NASA Activity Schedule

	Major Phases
1.	Gas Payload Reservation
2.	Payload Definition and Design Concepts
3.	Launch Services Agreement (Article I and II)
4.	Payload Accommodation Requirements Submission
5.	Payload Preliminary Design
6.	Preliminary Safety Data Package
7.	Payload Final Design
8.	Final Safety Data Package
9.	Payload Construction and Testing
10.	Phase III Safety Data Package
11.	Launch Services Agreement Addendum Signature
12.	Final Pre-flight Payload Preparation and Inspection
13.	Shuttle Flight
14.	Post-flight Payload Removal and Return
15.	Experiment Post-flight Activities

sequence. Due to the goals and directives of the GAS program, education experiments are given a higher priority and more positions in the rotation sequence. As of September 1999, 157 GAS payloads have flown aboard in 35 shuttle missions.

The process to flying a GAS payloads involves several steps. Table 2.2 outlines the sequence of major phases involved in launching a GAS canister (24).

The Launch Services Agreement (LSA) specifies all regulations and processes that must be followed, designates a reservation and canister number, and includes a generic description of the experiment and points of contact. Once the experiment and design are better defined, a Payload Accommodation Requirements (PAR) establishes basic payload requirements (size, weight, functions, events) and identifies all safety areas of concern. The PAR is discussed more thoroughly in the Section 2.2.2. Finally a Payload Integration Plan (PIP) is required for all shuttle payloads and includes all technical information on the experiment. Additionally, several Safety Data Package (SDP) reviews are conducted which detail the payload design, hazards, and analyses of the experiment. Specific safety considerations for this project are discussed in section 2.2.3.

2.2.2 Payload Accommodations Requirements. Since the LSA had been completed prior to this specific project, the next step in the GAS process is developing the PAR. The PAR is the document that begins to specify the type of experiment and equipment that will be flown. The PAR document "forms the technical agreement that details the unique aspect of (the) payload and its accommodations by the GAS Program (24)."

Once the draft PAR is sent to NASA, the Goddard Space Flight Center (GSFC) will assign a technical manager to the payload. The technical manager acts as a single point-of-contact on all matters pertaining to the payload. The draft PAR is included in Appendix A of this report.

The fifth step in the activity sequence is the preliminary design of the payload, which is the topic of this thesis. The next two chapters outline the requirements, options, decisions, and designs of each components of the experiment, as well as the assembly and interactions of the complete system. Although this design is not exhaustive in defining every detail of the design, it does describe the functions and interactions of the components and subsystems.

2.2.3 Safety. NASA has strict guidelines on the safety requirements for any payload on the Space Shuttle to ensure the safety of the astronauts, shuttle, and ground facilities. These requirements are specified in *Safety Policy and Requirements for Payloads using the Space Transportation System (17).*

The safety representative from the Goddard Space Flight Center represents the GAS experimenter at all NASA safety review boards. Therefore, GSFC requires numerous documents for review and approval to validate that the GAS experiment is safe. To aid in this process, GSFC publishes a document called *GAS Experimenter's Guide to the STS Safety Review Process and Data Package Preparation (16).* This guide includes a description of the GAS system, an overview of the safety

review process, a general hazard analysis approach, energy containment and hazard classification approaches, safety data package preparation, and battery information.

As can be seen in Table 2.2, many of the major milestones involve submitting safety paperwork for review and approval. However, one of the most critical portions of the safety review is the pre-flight inspection. At this point, just prior to canister integration, all components must be inspected by GSFC personnel. "If there are any portions of (the) payload that cannot be disassembled for inspection just before installation into the flight canister, special arrangements must be made to have them inspected earlier (24)." Additionally, any last minute changes in the experiment can cause the canister to fly on a later mission than scheduled.

NASA also encourages the implementation of "Safety Engineering" into the design of the experiment. Safety engineering is identifying any hazards that could penetrate the GAS container and endanger the shuttle or crew. After identification, the best option is to eliminate the hazard. If elimination is not possible, a method for controlling the hazard must be implemented. Finally, all controls should be verified as effective through test, analysis, and inspection.

After a safety review of the design, the experiment is designated as either Category B (Benign) or Category C (Controlled). Benign payloads are generally sealed, inert, with insufficient energy dissipation (under worst-case conditions) to breach the canister, contain non-hazardous materials, and fully contain the structure under the highest possible shuttle loads. Controlled payloads are those which carry toxic or hazardous materials in significant quantities, have sufficient worst-case energy to breach the canister in absence of controls. To ease the safety review and flight assignment processes, every effort is made to design the experiment within the Category B criteria.

The PAR, discussed earlier, is the first communication involved in the safety procedure. It identifies the basic design and components of the experiment and allows GSFC personnel to identify any initial safety concerns. It is important to submit

the PAR prior to any detailed design to minimize the possibility of major changes in the design. After the preliminary design is complete, the Preliminary Safety Data Package should be submitted. The Preliminary SDP is a more detailed review of the safety considerations and controls implemented within the experiment. After the final design is complete the Final SDP is submitted for approval. Finally, after the experiment is built and tested, the Phase III SDP is submitted and approved, the experiment is assigned to a specific launch.

III. Component Selection

3.1 Overview

Once the objectives, requirements, and constraints are defined, it is necessary to begin product reviews and component selection. The systems architecture shown in Figure 1.3 serves as a starting point for design decisions. This chapter will cover the independent issues dealing with each component. Each subsystem in the system architecture will be presented in the following manner; first an overview of the requirements, then a review of potential methods available, and finally a preliminary decision of the product that best meets the requirements.

Although all components effect the areas of power, weight, and cost, these system level considerations will be dealt with specifically in chapter 4. For simplicity, it is assumed that all decisions attempt to minimize power, weight, size, and cost. When the design integration occurs, preliminary selections will be reviewed to de-conflict any of the system-level requirements.

The majority of the design decisions are made through a logical, systems engineering minded process. However, some aspects of the design are decided by the project sponsor and the user (Air Force Institute of Technology). For the remainder of this report, the user will be considered the primary decision maker.

3.2 Structure

3.2.1 Requirements. The structure for the experiment will be dictated by the shape and configuration of each component. In the preliminary design stages, the structure is constructed of metal, most likely aluminum or stainless steel. The primary function of the structure is to support all of the components of the experiment. While minimizing the overall weight of the structure is a concern, the structural integrity of the experiment during all phases of the shuttle flight is the driving factor.

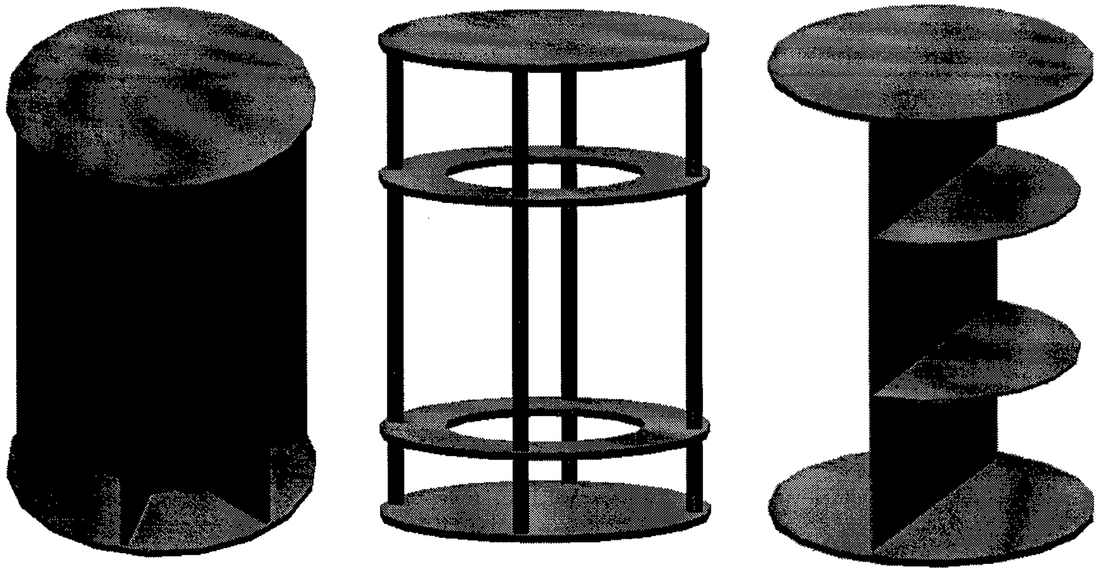

Figure 3.1 Potential Structural Designs

3.2.2 Options. Several concepts were developed as initial design considerations. Each alternative was designed independent of component size and selection, with the intent of maximizing the space available for the inflatable structure. The designs were divided into three categories; a shelf design where the experiment had several levels, a partitioned design that separated the diameter of the structure into several portion, and a hybrid of the shelf and partitions.

Figure 3.1 illustrate a potential designs for each of the categories. The first design shows the entire height of the canister divided into a number of equal angular sections, the second design shows the canister divided into shelves with the center removed, and the last design shows half the canister using the entire height and the other half consisting of shelves for support equipment.

3.2.3 Decision. The decision on the structural design is highly dependent on the individual components selected. The size, weight, and mounting methods of each component needs to be considered. Additionally, the overall size, weight, and

center of mass for the canister must be considered. Therefore, the decision on the preliminary design of the structure is finalized in chapter 4.

3.3 Inflatable Structures

3.3.1 Requirements. The user has specific applications for the data and future use of inflatable structures. As discussed in chapter 2, the near-term applications of large inflatable structures is in large-aperture radar and sun shields. Both of these structures will use long cylindrical tubes with a length to diameter ratio of approximately one hundred-to-one.

3.3.2 Options. To date, most inflatable structures have been spheres, tubes, rings, and trusses. The past inflatable structures covered in Section 2.1.2 and Section 2.1.3 illustrate these methods.

3.3.3 Decision. Based on the user requirement, the preliminary design will utilize cylindrical tubes. To maximize the amount of data collected, the design should maximize the overall length of the tubes and include as many tubes as possible. This will increase the amount of data collected from the experiment and increase confidence in the results. As a starting point, the user selected two-inch diameter tubes, which will provide a length to diameter ratio of around twelve-to-one. The tubes will be flattened along their length and z-folded for packaging.

3.4 Inflation Method

3.4.1 Requirements. The primary requirement for the inflation system is to provide sufficient pressure to inflate and maintain the structure until rigidization. Additionally, the inflation method should be benign to the GAS can environment so that no additional safety considerations are required.

3.4.2 Options. As noted earlier, the vacuum of space requires very low pressure for inflation. There are various methods used to "inflate" inflatable structures. The most basic method is high-pressure gas released into the structure to causes inflation. This type of inflation requires the gas supply, plumbing, and valves. The amount of gas required depends of several factors; mainly volume of the structure, the pressure required for inflation/rigidization, and the lifetime of the structure. The lifetime is important since traditional inflatables require sufficient makeup gas to compensate for outgassing or small leaks. Nitrogen gas is preferred because of its low weight and inert qualities. Recently, hydrazine has been investigated as a potential inflation gas. Although more volatile, hydrazine is used for fuel and attitude control on many spacecraft and by using hydrazine for inflation, the complexity and weight of the spacecraft may be reduced.

Sublimating powders are another method used for inflation. These powders were the used in the Echo satellite series (7) and are still used today for limited applications. The principle is that once in orbit, the powder is released into the interior of the structure and sublimes into a gas. The sublimating process stops once the proper temperature and pressure have been met. The excess powder then acts as makeup gas for self regulation. Unfortunately, the pressure created by these powders is only in the range of 10^{-5} to 10^{-6} atm.

3.4.3 Decision. The decision on inflation methods was made by the user. For the preliminary design, nitrogen gas at approximately four pounds per square inch absolute (psia) pressure was selected. The inflation system will require a cylinder of compressed gas, a distribution system, a control system of valves and gauges, and the connection to the inflatable structures. Since the purpose of the experiment is to determine the response of a rigidized, un-pressurized structure, the inflation gas must be vented once rigidization has occurred. The inflation system will be assembled from off-the-shelf pressure fitting and controls.

3.5 Rigidization Method

3.5.1 Requirements. When choosing a rigidization system, several material properties are desired. A high modulus after rigidization gives the tubes structural stiffness and strength. The process of rigidization should be reversible, in that the structure can be softened after rigidization, to allow for repeated testing. Also, the material should be highly flexibility to allow for packing and deployment. The coefficient of thermal expansion should be nearly zero, which gives the structure thermal stability in the high temperature variations of space. The material should be resistant to the space environment. And finally, the material should not change shape during the rigidization process.

3.5.2 Options. Although many rigidization techniques have been developed over the years, several methods are currently used. Each method uses different materials depending on mission needs. The four main approaches are: mechanical rigidization, chemical rigidization, UV rigidization, and thermal rigidization.

Mechanical rigidization is similar to the method used in the Echo satellite series (7). In this method, foil is sandwiched between two layers of protective material and fashioned into the desired shape. Once the structure is inflated, a second pulse of over pressure strains the foil beyond its strain point and causes the rigidization. The result is a structure that can withstand compression strain without buckling. This method was used on the L'Garde Inflatable Solar Array (7), where cylindrical tubes were inflated to deploy the arrays and then mechanically rigidized for strength. Although this method does not offer a very high strength-to-weight ratio, the rigidized system withstood considerable compressive loading before surface imperfections appeared.

Chemical rigidization offers the highest strength-to-weight ratio of all methods. In chemical rigidization, the materials are impregnated with resin or another material which is effected by the space environment. One of these is a water-soluble resin that is cured as the water evaporates from the material. The problem with this method

is the initial outgassing that is produced by rigidization. Another chemical method, called sub-Tg, is a resin which is pliable above a certain transition temperature and stiffens when cooled below the transition temperature. The "Tg" is the glass transition temperature, which can be tailored to the material.

UV rigidization is similar to chemical rigidization, except the rigidization is initiated by exposure to ultraviolet light. The advantage to this method is that the material can be sealed from UV until inflation; however the problem is that UV rays only penetrate into the first few layers of material, leaving the inner layers pliable. Additionally, the structure must be rotated to ensure uniform exposure and rigidization, which could be very difficult for the spacecraft.

Thermal rigidization uses the application of heat to cure the structure after inflation has occurred. The problem with this is the high amount of power required to warm the material. A new approach to inflation and rigidization has been taken by CTD, Inc. Their approach uses an elastic memory composite that is fabricated and fully cured at a specified temperature. Heat is applied to make the material pliable, and the material is folded into the storage configuration. Once the material cools, it retains the folded shape. Then, on orbit the material is heated again and the material reforms to its original shape, and no inflation system is needed.

3.5.3 Decision. The decision on inflation methods is determined by the user. For the preliminary design, the sub-Tg rigidization method was chosen. The inflatable tubes are manufactured from sub-Tg materials with specific thermal properties. The most important design variable is the transition temperature where the material becomes pliable. Due the wide range of temperatures experienced by GAS can experiments, the transition temperature must be chosen to prevent the possibility of the structure becoming soft once the inflation gas is vented.

The tubes can be heated either internally or externally. Internal heating use wires built into the tube to generate heat, whereas external heaters work like an

oven, warming the material inside the heat source. The internal method is most efficient since the heat is applied directly to the tube and radiates outward, however it requires more complicated manufacturing procedures. For the external method the opposite is true, more heat and time is required to warm the material, but manufacturing is easier.

After discussions with the tube manufacturers, it was decided the manufacturing difficulties of internal heaters were too large to overcome; therefore, an external heat source will be used. According to the GAS Experimenter's Handbook (24), the extreme range of temperature experienced from launch to landing is -160 to +100 degrees Celsius (^{o} C). Therefore the transition temperature should incorporate a margin of safety above +100^o C. Initially the factor of safety is chosen as 25 percent, and therefore the transition temperature is +125^o C.

3.6 Power

3.6.1 Requirements. The GAS payloads require that all power for the experiment be supplied by the experiment. The selection and design of the battery system has a direct impact on the safety certification of the experiment. The NASA requirements include fusing, diode isolation, and battery box design (16)(17). The specifics of the NASA requirements are discussed in the preliminary design of the power system.

The only additional requirement for the power subsystem is the total power required. This is measured in volts and ampere-hours. The amount of power required is driven by the design of the experiment and the individual power requirements of each subsystem. The battery source should be selected to provide the largest amount of power and longest lifetime, while occupying the minimum volume and weight. Shelf-life is another important consideration since the experiment may be stored for up to four months between integration and launch.

3.6.2 Options. The safety requirements of NASA quickly limit the options available for battery systems. The primary decision is whether to select a wet or dry cell battery. A wet cell battery uses liquid as the electrolyte and is often rechargeable by forcing an electrical current in the reverse direction of the discharge. Some common examples of wet cells are lead-acid (automotive), nickel-cadmium (household rechargeable), and silver-zinc (military). The evaluation characteristics for wet cell batteries are capacity, charge rate, and shelf life. A dry cell uses a moist paste as the electrolyte and are usually not rechargeable. Since the battery can fully discharge, the lifetime (or ampere-hour) rating is usually much higher. Some common types of dry cell batteries are alkaline, mercury cell, and reserve cells.

3.6.3 Decision. Considering all the safety requirements, past successful GAS experiments, and NASA acceptance, an alkaline D-cell system was selected. The size D batteries provide 1.5 volts (V) and have an approximate life of 17 ampere-hours (A-hr). By stringing multiple D-size batteries in series, which will be referred to as a battery cell, a higher voltage can be produced. With multiple cells in series, the total power is determined. Once the load of each component on their respective cell or cells is known, the lifetime of the battery system is calculated.

The size of each cell and the number of cells in series is driven by component selection and the power analysis (Section 4.10). By adding cells in parallel, the battery system is scalable to the requirements of the experiment. However, a size and weight penalty is assessed for each additional cell, and therefore the amount of power available is limited.

3.7 Command and Control

3.7.1 Requirements. The GAS canister is required to be a self-contained, self-controlled experiment. This means that any "active" experiment requires some type of command and control unit to direct operations. The GAS canister does

provide three relays that the shuttle crew may interact with, however these are primarily for powering up and down the experiment. Therefore, some type of computer is needed to provide the necessary functions of command and control. The computer will collect data and carry out an event calendar, which outlines the times and conditions for execution of the sequential actions within the experiment.

3.7.2 Options. There are essentially three basic types of computers that can be used for command and control; commercial off-the-shelf (COTS) , a custom 386/486/Pentium, or PC/104. A COTS computer would be simple and save time. However, a COTS system that meets all requirements would be difficult to find and likely would include extra features. Also, space-certified COTS systems are usually very expensive.

A computer using a 386/486/Pentium motherboard and peripherals is another option. This option allows the computer to be custom built to the specifications and there are many components that have been space certified. The primary disadvantage for these computers is their size.

The third option investigated is a PC-104 computer. PC/104 is a newer architecture that uses "modules (circuit boards) that can be stacked together to create an embedded computer system (21)." The PC/104 architecture has all the advantages of a custom built motherboard computer, at a lower cost than a COTS system, and many of the components have been space tested.

3.7.3 Decision. From discussions with prior GAS experimenters (i.e. VORTEX (1) and GAMCIT experiments), as well as discussions with the user, it was determined that the PC/104 architecture would provide the greatest balance of functionality, flexibility, cost, and size. There are dozens of manufacturers of PC/104 boards and hundreds of available pre-built boards. Also, custom built boards can be incorporated to perform specific functions for this experiment. Although some basic elements can be selected, the preliminary design will dictate which specific functions

and boards are required for the computer. Additionally, the function of the three relays and the specifics of the event calendar will be discussed in section 4.7.

3.8 Data Collection and Storage

3.8.1 Requirements. The primary objective of this experiment is to collect data on space inflated and rigidized structures. Therefore, the type and amount of data collected from the multiple sensors must be decided. Although sensor selection is discussed in section 3.9, the data from those sensors will be in an analog or digital format. The requirements are dependent on whether data collection must occur a high-speed or low-speed. Also, some of the sensors will require two channels to monitor one sensor, while others will only require one channel.

High speed data collection is considered anything above one kilohertz (1024 samples per second)(kHz). Low-speed data collection is taken at approximately one hertz (1 sample per second)(Hz). In general the low-speed data collection monitors the environment, which changes slowly, and the high-speed data collection monitors the experimental data, which changes quickly.

3.8.2 Options. Current methods of data storage offer several options for the type of storage media. There are two primary categories of media, volatile memory which is not saved when power is removed, and non-volatile memory which retains the data. Additionally, traditional hard-drives are considered a spinning device since the disk rotates, non-spinning media is considered safer with regard to shock sensitivity.

3.8.3 Decision. Due the "extreme" conditions of the Space Shuttle launch and orbital insertion, the data storage device should be non-volatile and non-spinning. Additionally, since a PC/104 system has been chosen for the command and control, it is logical to select a method of data collection and storage that works within the

PC/104 system. For data collection, there are a wide variety of analog-to-digital circuit cards available in PC/104 format.

Once the number of sensors, the sampling rate for each sensor, and the duration of data collection are determined, the required capacity of data storage can be determined. PC/104 systems offer a variety of methods for storing data. The *disk-on-chip* option allows up to 144 megabytes of non-volatile data storage on a single chip. If multiple chips are required, the system can incorporate a separate board that is solely made of memory chips. The number of chips used will be determined by the calculated data requirements.

3.9 Sensors

3.9.1 Requirements. For all sensors, the primary requirements are with regard to sensitivity and size. The sensitivity requirement specifies how many millivolts are registered per the unit of measurement. To attain accuracy in the readings, a higher millivolts per measurement value is desired. Since some of the sensors must be placed in confined areas, the size of each unit is also important. Additionally, all sensors are required to survive launch (10 times gravity, or +/- 10 g) and be operable in the temperature range of the GAS canister (-160^o to 100^o C). The specific requirements for each sensor are summarized in section 3.10, Table 3.2.

3.9.2 Options and Decisions. Due to their specific functions, each sensor has specific requirements. For each of the sensors, numerous options are available and a decision must be made on each. The following sections discuss each sensor and the appropriate decision.

3.9.2.1 Pressure. Although the experiment will operate in a vacuum, several pressure sensors are necessary. Two different sensor types are required; however, both have the same sensitivity requirements of approximately 0.01 atmospheres. With the exceptions of the battery box and the tubes during inflation,

the rest of the canister is open and vented through a pressure relieve valve in the experiment canister. Therefore, a single pressure probe is required to verify the environment inside the gas canister. Any COTS sensor that meets the requirements is acceptable, and the size of the sensor can be relaxed if necessary.

During the inflation process, the gas distribution system must be monitored to ensure proper pressure inside the tubes. A solenoid and pressure reducing valve will regulate the pressure within the tube to achieve inflation and a vent valve will release the pressure once rigidization has occurred. Both of these functions require sensors that are inline with the gas distribution system to monitor the pressure. Again, any COTS sensor that meets the requirements and interfaces with the gas distribution system is acceptable

3.9.2.2 Acceleration. One of the objectives of the experiment is to determine the response of a space rigidized structure to external excitation. Accelerometer are used to measure the vibration of the structure during the modal analysis. In order to collect the most data on the vibration of the tubes, a triaxial accelerometer will be placed at the free end of the tube. The required sensitivity and size for the tube accelerometers are 10 millivolts per g and less than one inch cubed.

There are two options for mounting the accelerometer, either on top of the tube or inside the tube. In order to maximize the overall length of the inflatable tube, the amount of equipment mounted on top should be limited. Therefore an internally mounted accelerometer is preferred and a trade off between size and sensitivity must occur in selecting an accelerometer to use.

The excitation described above is intentionally produced by the experiment. Any external excitation or vibration of the shuttle must be monitored to evaluate the data collected. Therefore, an additional accelerometer is required to measure any vibration of the canister and experiment. For the experiment structure ac-

celerometer, an accuracy of 20 millivolts per g is desired; however, size is no longer the driving constraint since the sensor can be mounted anywhere on the structure. For both accelerometer applications, a COTS sensor that meets the requirements is acceptable.

3.9.2.3 Voltage. During the execution of the experiment, the battery system will be discharging. Although testing will verify the appropriate size of the battery system, a voltage sensor is beneficial to monitor battery charge and troubleshoot any problems. A single voltage measurement of the total battery systems, within one-half a volt, should provide adequate information in case of any irregularities in the experiment's execution. Any COTS sensor that meets the requirements is acceptable.

3.9.2.4 Static Position. After inflation, the static position must be measured to determine if the tube is fully inflated. Due to the dynamic tests that must be accomplished, a non-contact method must be used. The final position of the rigidized tube needs to be determined to within one millimeter. Several methods of measuring the distance were considered and the options were placed into two categories, measurement by laser or video.

Laser displacement sensors use two types of measurement techniques. Either time differential, where the time for a pulse of light from the sensor to travel to the target and reflect back to the sensor, or light intensity, where the sensor calculates the distance based on the intensity of the laser reflected back. Both methods are effective at measuring moderate distances at very high accuracy.

Additionally, there are several designs for each type of laser displacement sensor. A triangulation sensor emits a laser perpendicular to the surface being measured and then reads the reflected light at an angle slightly off perpendicular. This allows a more accurate calculation of distance based upon a focus laser source and a larger collection area. The fiberoptic design uses a single fiber optic cable to both emit the

laser and collect the reflections. The advantage of a fiberoptic design is that the end of the cable can be located in tight spaces, while the support equipment is mounted elsewhere.

The second method of measuring distance is the use of a digital video camera. The camera can either take continuous video or still frames of the inflated structure. Within the area of video measurement, two alternatives were examined. The first alternative uses a visible scale placed inside the canister and viewing the structure from an angle. As the structure inflates, the height can be compared to the scale and extrapolated. A still frame of the rigidized structure should allow a determination of its final height; however, the method is not very precise and has difficulties determining any angle in structure.

The other alternative is to place the camera directly over the top of the tube looking downward. An image can be placed on top of the structure and the camera takes several still shots as the structure inflates. By knowing the field of view of the camera, the number of pixels in each photo, and the actual dimensions of the image, the distance and angle of the image can be calculated. This is done by counting the number of pixels of the image in the photo and comparing it to known reference data on how many pixels should be visible. Section 4.6.5 details how the distance and image are determined.

In comparing the multiple options available, several criteria were used. The size, weight, power and temperature requirements of each option were evaluated, as well as the accuracy of the measurement device. Although the laser displacement sensors offered the highest accuracy, any option required the sensor be heated and some systems have large control units. The overhead video camera seems to offer the best combination of accuracy, power, and size. Additionally, the user had initially expressed a desire for video to show the inflation process and for analysis in the event of a problem with inflation.

Therefore, a digital video system will be incorporated into the design and a laser displacement system will be used in calibrating the ground testing and calculations for displacement. Since a PC/104 computer system has been selected for command and control; it is logical to use a camera that will interface with the computer system. If possible, three cameras will be wired into one PC/104 video card to capture and download images into the data storage device.

3.9.2.5 Temperature. Temperature data is required in numerous locations throughout the experiment. First, sensors are required to profile the heating and cooling of each tube through the inflation and rigidization steps. In order to monitor inflation and rigidization, small (i.e. less that one-half inch area) temperature sensors are attached to the inflatable tubes. Depending on thermal profiles of the heating and cooling rates, the temperature changes are expected to be sufficiently slow so that the data can be sampled at a slow rate. Any COTS temperature sensors that meets the requirements is acceptable.

In addition to the tube sensors, several additional sensors should be mounted throughout the canister to observe the environment. These sensors should have the same sensitivities as the sensors on the inflatable tubes, however the size requirement may be relaxed if necessary. At a minimum, the temperature of the computer and two locations within the canister should be collected. The computer temperature will be important in determining any problems with operations, and the two environmental temperatures can be used to determine the steady-state conditions within the canister. The number and location of the extra temperature sensors will be determined once the data collection and storage capacity is determined.

Secondly, sensors are necessary to maintain appropriate temperature of specific components. Once the Space Shuttle achieves orbit and opens the cargo bay, the temperature within experiment could drop significantly. Several key components must be kept above 0^o C in order to guarantee correct operations. These compo-

nents include the battery box, computer, and digital cameras. If the temperature of the batteries drops too low, the performance and lifetime are drastically effected. Likewise, if the computer is too cold, components and circuitry may freeze and it may not operate correctly. With respect to the cameras, the CCD component must be kept within a specific temperature range to function.

Although these components may require heating to maintain an adequate temperature, once operations begin the components will generate their own heat. Consequently, the heaters cannot remain on the entire duration of the experiment or overheating may occur. The solution to this problem is found in using self-regulating heaters. Once the temperature of a component drops below a specified point, the heater turns on and warms the component until the component is within correct parameters again. Several types and manufacturers of thermal controllers were evaluated. Based largely on repeated success in a similar GAS application, Minco Corporation heaters and controllers were selected. Also, the Minco heaters are self controlled and don't require any interface with the computer.

3.10 Summary of Preliminary Design Decisions

Once the design options had been evaluated, a preliminary design review was presented to the user for approval. The purpose of the review was to achieve consensus on initial component selection. This allowed the integration and design analysis to proceed with less risk of a substantial change in components. It should be noted that in most cases, the type of component and necessary requirements were decided in the preliminary design review. Specific model and part numbers are not presented, which allows the future assembly team discretion in what to purchase and flexibility to choose among several manufacturers.

Table 3.1 shows a summary of all decisions that were made in the first preliminary design review. Table 3.2 summarizes the specific requirements for each sensors sensitivity and size. After the component selections and design review were

completed, the individual components must be assembled into a functioning systems that meets the system level requirements and constraints.

Table 3.1 Component Selection Decisions

Component	Decision
Structure	Layout driven by component selection
Inflatable	Tube with 2 inch diameter, 22 inch length
Inflation System	Nitrogen gas at 4 psia
Rigidization System	Sub-Tg rigidization with 125° C transition temp
Power	Alkaline D-size batteries, scaled to power requirement
Command & Control	PC/104 Architecture Computer
Data Handling	Non-volatile Memory Chips in computer
Sensors	
Pressure	COTS sensor that meets requirement
Acceleration	COTS sensor that meets requirement
Voltage	COTS sensor that meets requirement
Force	COTS sensor that meets requirement
Static Position	Digital Camera with optical target
Temperature	COTS sensor that meets requirement
	Minco Heaters to maintain environment above 0° C

Table 3.2 Sensor Requirements

Sensor	Location	Sensitivity	Size
Pressure	Tubes	0.001 atm	1/4 inch fitting
	Environment	0.001 atm	n/a
Acceleration	Tubes	10 mV/g	$\leq$ 1 inch cube
	Environment	20 mV/g	n/a
Voltage	Power Supply	0.5 V	n/a
Static Position	Flight	1 mm	$\leq$ 2 inch height
	Ground Testing	5 μm	n/a
Temperature	Tubes	0.5° C	0.5 inch square
	Environment	0.5° C	1 inch square
	Components	1° C	internal

IV. Preliminary Design

4.1 Overview

Using information from the design review, component selection, and analysis, the preliminary design shown in Figures 4.1 and 4.2 emerged. This design is the result of an iterative process which included varying component packaging and placement. Although the preliminary design does not specify cabling and connections, areas of the experiment are available for cable routing and connections. Additionally, initial drawings of parts requiring custom manufacture are listed in Appendix E.

4.1.1 Concept of Operations. The RIGEX system is a self-contained, automated GAS experiment intended to collect data on space inflated and rigidized structures. After launch, it is designed to maintain a minimal environment until the Space Shuttle crew initiates the startup process. The pressure is regulated by a filter relief valve which vents the canister during ascent and repressurizes during reentry and landing. The thermal environment is maintained through autonomous heaters that are power through a baroswitch. As the shuttle reaches 50,000 feet altitude, the baroswitch activates the main power relay for the heaters.

At a specified time, the astronauts will activate the experiment through a command relay, which powers the computer. The computer then proceeds with control, operations, and data collection until either the event calendar is completed or the experiment is deactivated. During this time, the environmental sensors collect data on the canister temperature and pressure, as well as the battery voltage.

As the inflation and rigidization process is begun, heaters warm the inflatables above their transition temperature. Once warmed, nitrogen gas slowly inflates the structure, while the video sensors record the inflation. After inflation, the structure will radiate and cool until an equilibrium temperature is achieved. After the rigidiza-

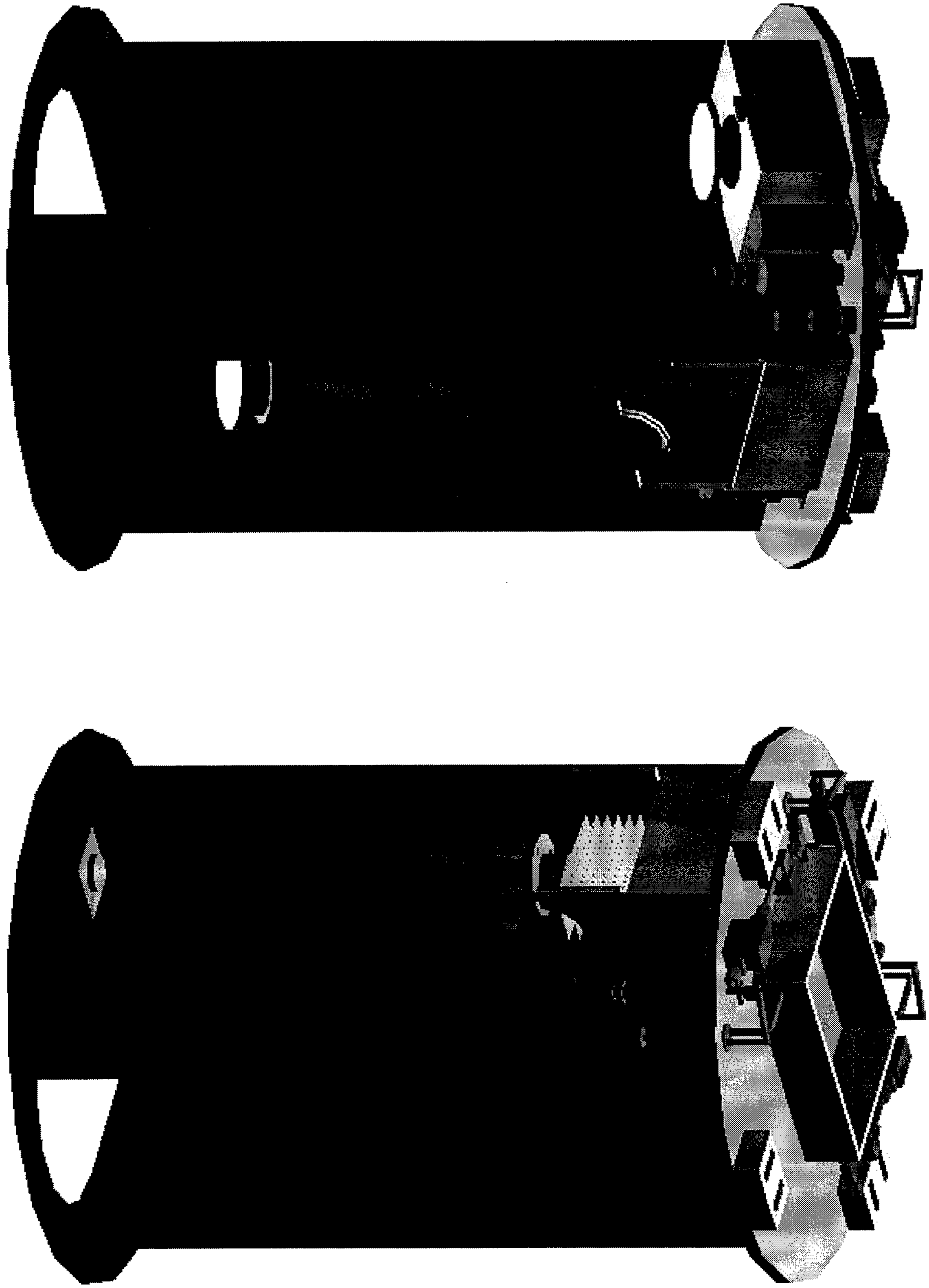

Figure 4.1 Preliminary Design- Shaded

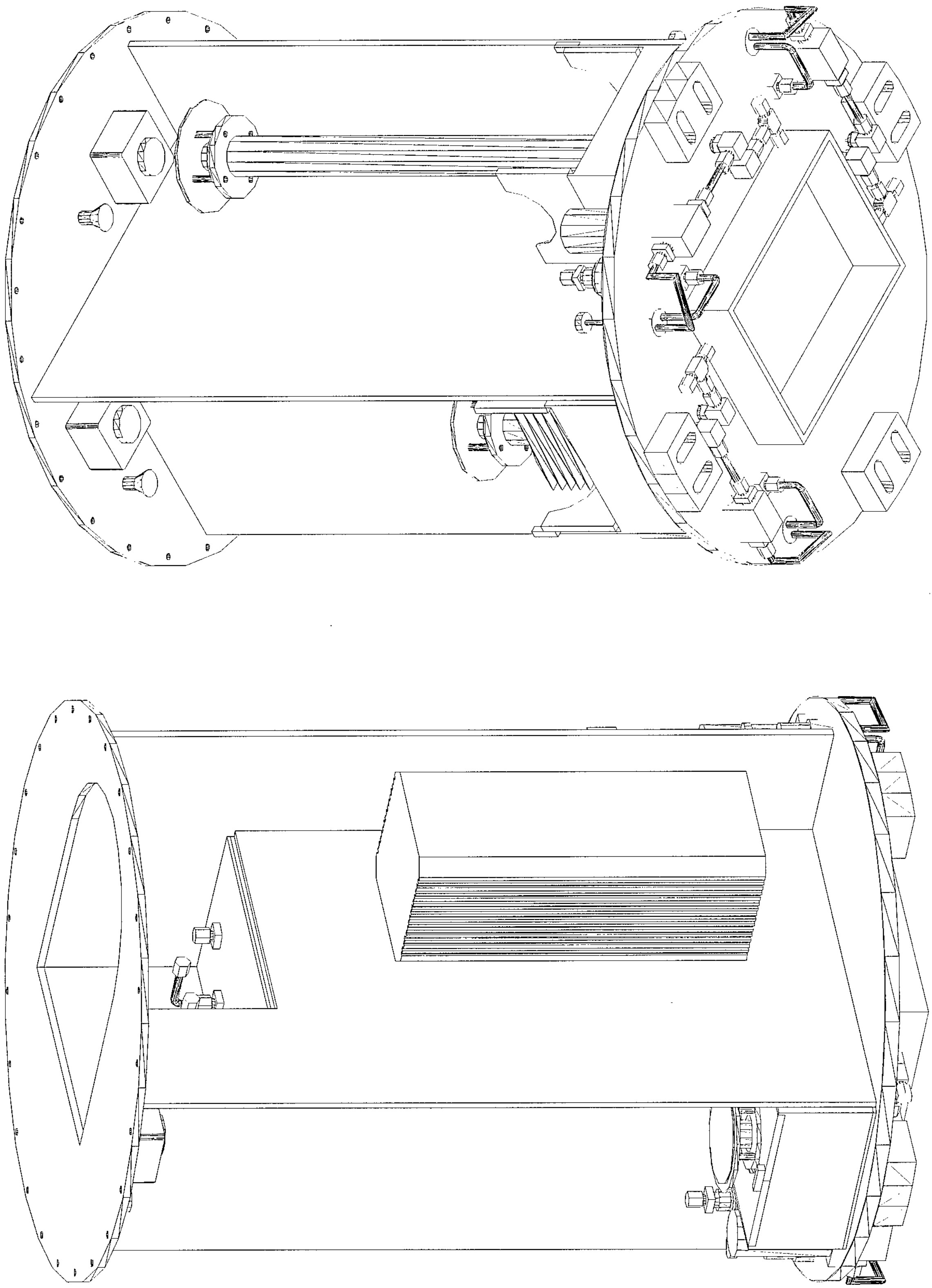

Figure 4.2 Preliminary Design- Wire Frame

tion is complete, the inflation gas is vented. During the entire process, temperature, pressure, and displacement sensors will collect data.

To test the structural properties of the rigidized structure, an excitation device is placed at the cantilever end of the inflatables to cause vibration. During each excitation cycle, the accelerometers collect data on the modal response of the inflatable structures. Once all activities in the event calendar are complete, the computer will enter an inactive state until power is disconnected for reentry. This is only an overview of the operation process that is fully explained in section 4.7.3.

In the following sections, the preliminary design is broken down into major components and described in more detail. The major components follow the system architecture shown in Figure 1.3. The design of the structure, inflatables (structures, inflation, and rigidization), power, sensors, command and control, data handling, and heater systems are explained. Then power, weight, and cost analyses are performed for the entire system.

4.2 Structure

As stated earlier, the design of the structure is a driven by component size, weight, and mounting methods. Additional design constraints are imposed by NASA as to how the experiment is assembled with the GAS canister and integrated into the Space Shuttle. The GAS canister is an aluminum cylinder with a top and bottom plate. Figure 4.3 shows the assembly of the Gas components, including the experiment mounting plate, interface equipment plate, experiment, container, and covers.

4.2.1 Experiment Mounting Plate. The top plate of the GAS canister is called the Experiment Mounting Plate, or EMP. The EMP serves three main functions, it seals the top of the canister, provides the mounting surface for the experiment, and provides venting of the canister. The EMP is designed by NASA

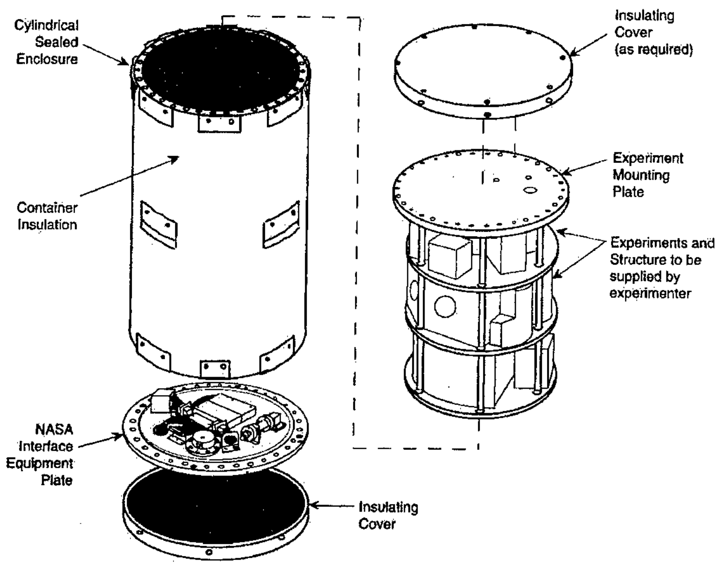

Figure 4.3 GAS Container Concept (24)

to provide a standardized integration design for all GAS experiments and cannot be modified for the design. Once the experiment is mounted to the EMP, it is lowered into the cylinder shell and secured.

4.2.2 Bumpers. Once the EMP is secure, the experiment is cantilever inside the canister and requires additional support. The lateral support bumpers provide that support. *The GAS Experimenter Handbook* requires at least three adjustable bumpers be evenly spaced around the circumference of the experiment and that each bumper have a minimum contact area of 4 square inches. There are four bumpers attached to the bottom plate of the structure. A more detailed description of the bumper requirements can be found in the handbook (24).

4.2.3 Interface Equipment Plate. After the bumpers are adjusted and secured, the Interface Equipment Plate (IEP) and insulating cover are attached to the bottom of the canister. The IEP provides the connections for the power relay, command relays, barometer switch, and a general support computer. The IEP is

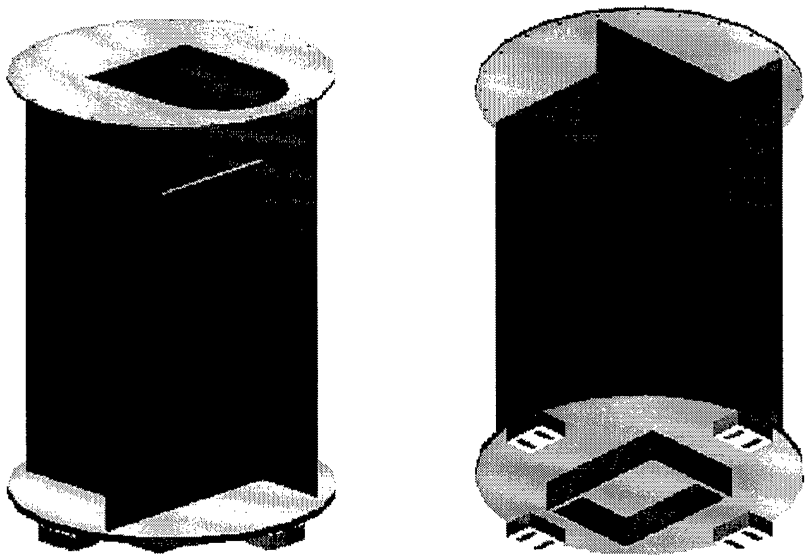

Figure 4.4 Experiment Structure

then sealed to the bottom of the canister, the canister is purged with dry nitrogen gas at one atmosphere, and the assembly is stored until integration.

4.2.4 Experiment Structure. The two factors which had the greatest impact of the final structural design were maximizing the overall length of the inflatable structures and maintaining the center of gravity for the experiment. Therefore it was logical to install the inflatables along the long axis of the experiment and balance the heaviest components around the centerline of the experiment. Since the batteries account for a large portion of the total weight (see section 4.11), they are place along the centerline; with one inflatable structure on each side and the additional support equipment on the fourth side.

Figure 4.4 shows the structure from two view points. The structure is constructed of one-quarter inch thick aluminum, with the exception of the bottom plate which is one-half inch thick. The thickness serves two purposes, it gives strength to the structure and allows for secure mounting of all components. The bottom plate is thicker because components are mounted to both sides of the plate. Additionally, all

parts are welded at their joints to increase overall strength. If weight becomes a driving factor for the design, the thickness of the structure can be reduced. To simplify the design, standard mounting screws should be used wherever possible (recommend #10-32 stainless steel socket head cap screws).

The top plate connects to the EMP provided by NASA, with the top hole providing clearance for the venting holes and the battery purge ports. The height of the experiment is divided into five sections, four equal size wedges and the center area which provides a reservoir for the battery box. Three of the wedge areas are used for inflatable structures, ovens, and inflation systems. The forth wedge is used for the experiment support equipment. The top side of the bottom plate provides attachment for the inflatable structures and the bottom side is used for the inflation system and bumpers. The square base is designed to support the experiment during assembly and testing, and to protect the inflation system.

4.3 Inflatable System

The next element in the system architecture are the inflatable systems. The user made the primary decisions on the inflatable structures, the inflation method, and the rigidization method. However, the integration of these decisions was not specified. After restating the requirements for each component of the system, the preliminary design is proposed.

4.3.1 Inflatable Structures. The user decided on inflatable tubes with a diameter of 1.375 inches. The tubes are made of a graphite-fiber reinforced thermoplastic material that is produced by the L'Garde Corporation. The diameter was reduced from the original 2 inch diameter to conform with L'Garde's existing manufacturing capabilities. Additionally, the experiment is designed to maximize the length of the inflatables.

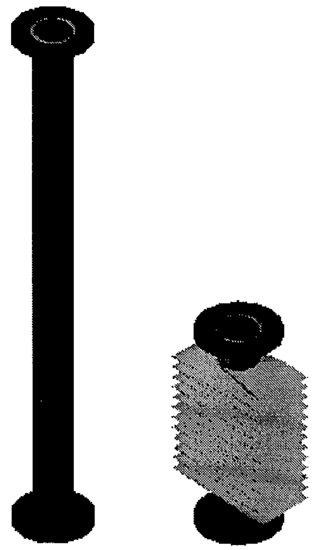

Figure 4.5 Inflatable Structure Assemblies

To mount the tubes within the structure and to attach instrumentation to the free end of the tubes, top and bottom flange were designed. The design of each flange are similar. The differences are that the bottom flange is open to allow inflation and venting, and the top flange is capped to help seal the tube.

The bottom flange also seals the tubes for inflation by using a Viton O-ring between the flange and the structure and an airtight adhesive material to connect the tube material to the flange. The manufacturer recommended a contact length of 0.75 inches to successfully secure the tubes to the flange. Therefore the effective length of the structure is the actual length minus the contact length on each end. Using an approximate length of 22 inches, this gives an effective length of 20.5 inches and a length-to-diameter ratio of around 15-to-1.

To package the inflatable structures, the user decided on an accordion fold (or z-fold) where the tube is flattened along its length and folded back-and-forth. This method allows for compact packing and connections at both ends of the structure, while providing some type of controlled inflation. Figure 4.5 shows two tube configurations, inflated and packaged.

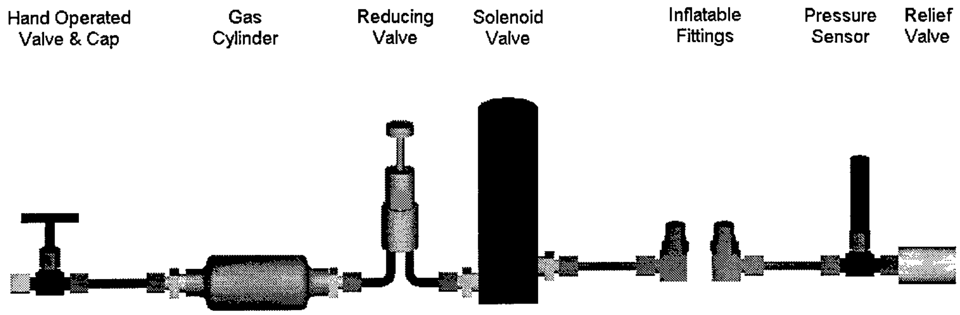

Figure 4.6 Inflation System

4.3.2 Inflation System. The inflation method chosen by the user is a nitrogen gas system. The gas distribution system consists of a pressure cylinder that will hold the gas, a distribution system of tubing and valves to control gas flow, and connections to the inflatable structures. Figure 4.6 shows the component layout for the gas distribution system.

There are two options for pressurized gas storage, a single cylinder that stores enough gas for all three tubes or individual cylinders for each tube. The advantages to a single cylinder are simplicity, weight, and cost. However, a single failure either in the cylinder or in any tube could prevent any inflation and nullify the entire experiment, whereas individual cylinders have less probability of all failing in a single flight. Until cost and weight become binding constraints, the individual cylinder method is preferred.

Each cylinder is open on both ends, with a capped hand-operated valve for charging on one end and a series of valves and pressure sensors connected to the inflatable structure on the other end. Moving from the cylinder towards the inflatable structures, a pressure reducing valve is used to maintain a preset pressure on the output side of the valve. The pressure reducing valve used should have a small enough orifice to provide a controlled inflation. Initially, the inflation pressure is assumed to be approximately 4 psia. As initial testing is conducted, the pressure will be refined to provide the optimal conditions for inflation and rigidization.

After the reducing valve, a 24 VDC solenoid acts as a primary seal to contain the pressurized gas in the cylinder. The solenoid is normally closed, meaning that when there is no voltage applied to the solenoid, the valve is closed. To minimize the size and weight of the inflation system, it would be best to find one component that performs both the solenoid and pressure reducing functions. However, at this time no such component has been found.

The distribution system will terminate with a fitting to a threaded through hole in the bottom support structure, directly below the tube. The gas will then flow into the inflatable structure. After rigidization occurs, the inflation gas must be vented to return the inside of the inflatable structure to a vacuum. Initially, this venting occurred through a solenoid valve connected to a second fitting and threaded hole below the tube.

The inflation solenoid (normally closed) is de-energized to close the supply of pressurized gas. Then the vent solenoid (normally open), which was closed during inflation, is de-energized to open the valve and vent the tube. Between the inflatable structure and the vent solenoid, a pressure sensor is attached to monitor the pressure throughout inflation, rigidization, and venting. The vent valve remains open throughout the remainder of the flight to allow the tubes to pressurize equally with the canister during landing. The normally open vent valve acts as a fail safe to ensure the tube equalizes with the canister during re-entry and landing. If the tubes do not vent, the external pressure could cause the tube to fail and not be available for post-flight analysis.

An alternative to two solenoids is a single solenoid with two inputs and one output. When open, the first input is connected to the gas cylinder and passes through the solenoid to the inflatable structure. When closed the second input is left open to the experiment and inflatable structure is vented. In this configuration, the second pressure fitting on the inflatable structure is connected only to the pressure sensor and a relief valve. This is the option shown if Figure 4.6.

To prevent over pressurization of the inflatable structures, a pressure relief valve is also attached to the vent plumbing. If the pressure rises above the relief valve setting, the relief valve will open. As the temperature of the inflatable structure changes, the pressure of the gas also changes. Initially, the inflation gas is relatively cold inside the pressure cylinder. When released into the inflatable structure, the gas is warmed by the structure and the pressure will rise. As the structure cools and becomes rigidized, the gas will cool and the pressure will decrease. Additional gas from the cylinder will maintain the required pressure until rigidization is complete.

The layout of the inflation system is not critical. The important factors are ensuring the appropriate components are accessible and no interference with the inflatable structures. Initially, all inflation components were mounted on the under side of the bottom plate. However, the size of the components selected caused the layout to be very difficult. The current design shown in Figure 4.1 has the components mounted to the top of the bottom plate, next to the oven. Once the components for the inflation system are in-hand, the optimal layout and assembly can be determined.

4.3.3 Inflation Calculations. To determine the required amount of inflation gas, the ideal gas law is used. The calculations for the required inflation gas are given in Appendix B. To calculate the maximum amount of gas needed for the entire inflation and rigidization process, the worst-case temperatures at each phase are assumed. Using a required inflation pressure of 4 psia inside the tubes, and assuming at inflation the minimum temperature of the GAS canister, 0.01571 moles of gas are needed for inflation.

After inflation, the gas will reach an equilibrium temperature with the tube, which can be no greater than the maximum temperature of the oven. As the gas is heated, the volume and remains constant and therefore the pressure increases. However, the relief valve maintains the appropriate pressure by venting gas from the

tube into the canister (which is vented into the shuttle cargo bay). At the maximum tube temperature, 0.00419 moles of gas are needed to maintain 4 psia.

After the equilibrium temperature is reached, the tube and the gas cool for rigidization. As the gas cools back to the original temperature, the pressure will decrease; however, the pressure reducing valve maintains pressure by allowing additional gas into the tube. Eventually the structure and the gas return to the equilibrium temperature of the canister. Subtracting the gas in the tube at the maximum equilibrium, 0.01152 moles of gas are needed to maintain pressure during rigidization.

Adding the inflation and rigidization quantities, and then multiplying by a safety factor of 1.25, the required quantity inflation gas is 0.03403 moles. Assuming a storage cylinder of 50 cm^3 and the maximum temperature of the canister, the maximum pressure inside the cylinder is 347 psia. This maximum pressure is well below the 1800 psia threshold of the cylinder. Finally, assuming the gas and cylinder are at room temperature (32^o C) during charging, each storage cylinder must charged to 250 psia during the integration of the experiment and the gas canister.

4.3.4 Rigidization System. The user selected the chemical rigidization method known as sub-Tg. The inflatable structures will be manufactured with specific material properties and a specified transition temperature. The preliminary transition temperature of 125^o C was chosen to conform with the NASA data provided for extreme GAS temperatures; however, if more accurate data is received from NASA or manufacturing requirements change, the transition point can be changed. The amount of power required for heating the structures is anticipated to be a large portion of the power budget; therefore, the lowest safe transition temperature should be used. Using the typical data from NASA, GAS experiments usually experience temperatures between -50^o C and 65^o C (which gives a transition temperature of 81^o C). Ideally, the tubes would be pliable at room temperature and rigid at the cooler temperatures of space.

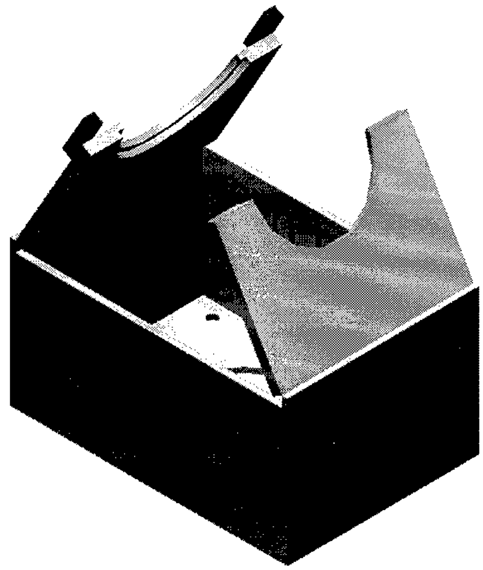

Figure 4.7 Inflatable Structure Storage and Heating Elements

To warm the structures above the transition temperature, heaters are required. An external heater capable of heating the material in the packaged configuration is required. To maintain uniformity and simplicity in the design, MINCO heaters similar to those explained in section 4.9 are used.

A heating element is placed on the inside walls of the storage box/oven, as shown in Figure 4.7. The oven should be made of a insulator material that can withstand high temperatures and minimize conductive heat transfer. Potential material selections for the oven are low conductance metals, high temperature thermoplastics, or a combination. The center hole allows the inflatable structure flange to mount and seal directly to the structure and the four mounting holes are threaded to mount the oven onto the structure.

The cover of the oven/storage box is a protective cover for the inflatable structure before inflation. The cover is grooved to hold the top flange of the inflatable structure when closed. The cover is spring loaded and held into place by two retractable pins. When the pins are released, the springs will force the top open and allow the structure to inflate.

A direct calculation of the temperatures and duration required for heating are difficult to obtain; therefore, the proper settings should be determined by profiling the heating of the packaged tubes in a controlled setting. By placing multiple sensors at specific points within the folded structure, an accurate temperature profile can be determined over the time required for heating. A starting point for sizing the heaters is provided by the Minco application guides. *Minco Application Aid No. 21* outlines the calculations used in estimated the power, temperature, and physical size of the heaters (15).

4.4 Excitation System

An excitation system for use in the modal analysis of the rigidized structures is being developed for the experiment. Although the integration of the system into the experiment is important to the preliminary design, the specific design of the system is not. A brief overview of the system is included to explain the basic integration into the preliminary design.

The purpose of the system is to provide an arbitrary excitation to each rigidized tube. The computer will initiate the excitation with a signal from a digital-to-analog output. The signal is sent through an amplifier to boost the signal strength, and then to a piezo-electric device in the excitation system. The amount of excitation is measured by a force gauge between the system and the tube. The response to the excitation is measured with an accelerometer mounted at the cantilever end of the tube. Power, size, and weight requirements of the excitation system will be integrated into the design at a later time.

Initially, it is assumed that the excitation system will excite two axes of the tubes independently and measure the response of each. Two axes are required to determine if the seam of the structure has any effect on the modal response. The tube will be excited along each axis for a specified period of time, which is called one cycle.

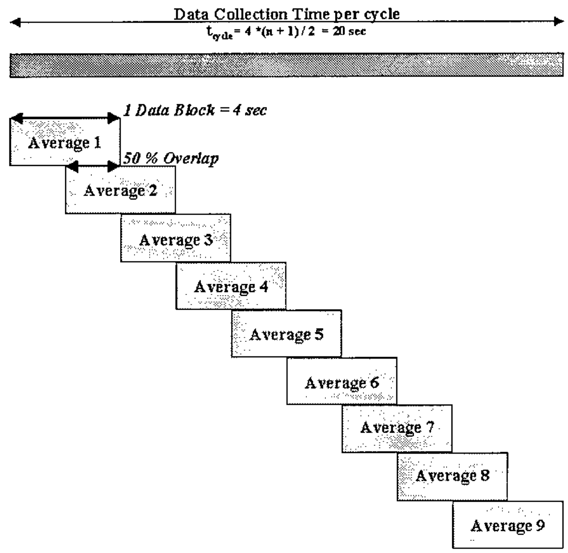

Figure 4.8 Excitation System Data

During post-flight analysis, the data collected from each cycle will then be segmented into blocks and averaged. In order to minimize the negative effects of averaging, an overlap will be used in segmenting the blocks. Assuming a cycle time of 20 seconds, 50% overlap, and a block size of 4 seconds, nine data averages will be used to determine the modal response to the excitation (see Figure 4.8).

4.5 Power

After the structure and the inflatable systems, the next component of the experiment is the power system. The power system consists of the battery cells, the battery box, and the power wiring.

4.5.1 Battery Cells. As discussed in chapter 3, the electrical power for the experiment is provided by alkaline D-cell batteries. The battery system will provide all the required power for the duration of the shuttle flight. Initially, twenty batteries are arranged in series to produce a 30V cell with a lifetime of 17 A-hr. The preliminary design allows for eight of these battery cells inside the battery box.

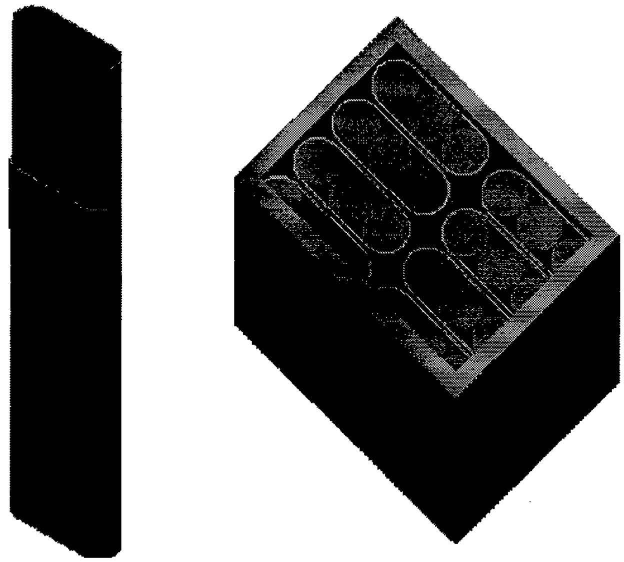

Figure 4.9 Battery Cell and Box Configuration

Figure 4.9 shows a cut-away view of one battery cell and the configuration inside the battery box

A 30V cell was selected to provide maximum flexibility in the experiment. Most of the components that requires power will accept an input voltage of 28 to 30 volts. However, smaller cells can be used to provide the necessary voltage or current for specific components. The battery cells provide power to three main areas of the experiment; the computer, rigidization heaters, and environmental heaters. All of the sensors are powered through the computer, which contains an internal DC power converter connected to the computer battery cells.

For those components requiring more or less power, DC to DC power converters can be used. The DC/DC power converters take a given input voltage and convert it to single or multiple outputs with specific output voltage and current. For example, given a nominal 28 volt input, a 30 watt converter could provide a single output or 5V at 6A (30W) or two outputs of +15V and -15V at +/- 1A (30W). DC/DC power converters give the design the flexibility of using the standard battery cell to provide component specific power.

Since the voltage and power requirements cannot be determined until specific components are purchased, the battery system is designed with some flexibility. Either the battery cells can be sized specifically for the components that they are servicing, or converters can be used with the standard battery cells. Regardless of which design is chosen, there are specific safety requirements regarding the design of the experiment's battery system.

4.5.2 Battery Box Design. The complete battery system is contained in a battery box and in accordance with NASA safety guidelines (*Proper Battery System Design for GAS Experiments* (16)). The battery box has several design requirements imposed by NASA; including fuse and wire size, materials, and venting.

NASA requires that each battery cell be fused to protect the fuse wires and battery. A reliability factor of two is used in selecting each fuse; therefore, if the maximum current draw of the wire is 5 amps, the fuse size is 10 amps. Another fusing decision is whether to use fast-blow or slow-blow fusing. The choice between the two types depends on how dangerous the line current is. If anything above 10 amps will damage the component or experiment, then a fast-blow fuse is selected; however, if the component can withstand a short duration spike of 10 amps and continue to function, a slow-blow fuse is selected. Individual components may also be fused to protect them from over heating.

Table 4.1 is a reproduction of the NASA wire size table that outlines the maximum current dissipation for three insulation ratings. Due to outgassing, Kapton insulated wire is recommended for all connections and wiring. The table lists the wire ratings base on ground and space use. The maximum current in space is much lower due to the lack of conductive heat transfer is space. Since this experiment requires a vacuum environment, the space ratings should be used. To choose a wire gage for each connection, determine the desired insulation rating and the current

Table 4.1 NASA Wire Ratings for Space and Ground (16)

Wire Gage	Current Rating (Amps) space / ground				Wire Gage	Current Rating (Amps) space / ground		
	150° C	175° C	200° C			150° C	175° C	200° C
0	235 / 369	285 / 405	340 / 450		14	19 / 56	23 / 62	26 / 65
2	155 / 270	190 / 300	215 / 340		16	14 / 39	17 / 42	20 / 45
4	115 / 220	140 / 250	160 / 280		18	13 / 37	15 / 39	17 / 42
6	85 / 170	100 / 180	120 / 190		20	8 / 25	10 / 27	12 / 29
8	60 / 120	71 / 130	80 / 150		22	6 / 19	8 / 20	9 / 22
10	37 / 80	42 / 90	51 / 100		24	5 / 14	7 / 15	8 / 16
12	29 / 62	34 / 68	38 / 74		26	4 / 13	5 / 14	6 / 15

draw on the wire, and then use the NASA table to determine the minimum gage size.

There are two options for venting the battery box, venting into the canister or into the shuttle cargo bay. If the battery box is to be vented into the canister, "a free volume analysis must be performed which shows that under the worst possible conditions, a combustible atmosphere in the container is not possible (16)." If the battery box is to be vented to the cargo bay, the box must be airtight to prevent any hazardous gases from venting into the GAS canister, and the integrity of that seal must be tested. Since the entire canister is to be vented to zero atmosphere throughout the flight, the user should check with NASA to determine if an unsealed battery box vented through the pressure relief valve meets the venting requirements.

If the battery box must be vented, the top should make an airtight seal with the battery box and contain a pressure test port. Prior to acceptance, the battery box will be pressurized to two atmospheres and sealed for 24 hours to verify the integrity of the seal. The top of the battery box should also contain two connections and the necessary plumbing to connect the battery box to the NASA provided pressure valves and fittings. During integration, battery box is purged with dry nitrogen and sealed at one atmosphere. During flight the pressure valves will vent if the pressure differential between the battery box and the cargo bay is above 15 psia. Figure 4.10

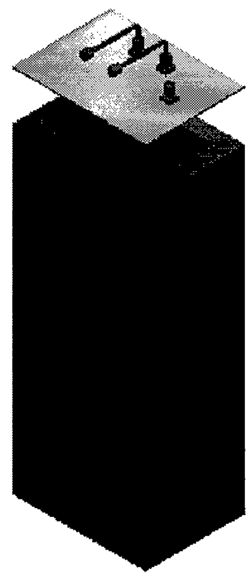

Figure 4.10 Battery Box

shows the preliminary design of the battery box and the vacuum fittings, assuming a vented box is necessary.

The battery box is to be constructed of aluminum plates welded together to form an airtight and leak proof box with a removable top. The interior of the box must be lined with a non-conductive, electrolyte-resistant coating. This coating isolates the battery from contact with any of the structure or GAS canister. Additionally, the inside of the box contains electrolyte absorbing material, which is needed in case of any leaks in the corrosive materials inside the battery. The material also helps pack the battery box and eliminate any movement of the cells.

So far, the experiment structure, the inflatable tubes, inflation and rigidization system, and the power system have been discussed. In order to collect data throughout the experiment, sensors are needed to monitor the environment and the tests conducted.

4.6 Sensors

Recall from the sensor requirements table (Table 3.2), acceleration, pressure, temperature, displacement, and voltage sensors are included in the preliminary design review. In addition, a force sensor is included in each excitation system. Once a specific sensor has been chosen, it must be integrated into the design to maximize the effectiveness of the data collected. The sensors are broken up into two categories; environmental and experimental. Because there are many different manufacturers of each sensor, the actual selection of the flight hardware is left to those working the manufacturing and assembly of the experiment. For each sensor, the application and integration into the design are discussed.

4.6.1 Acceleration. There are two separate applications for accelerometers within the experiment. One accelerometer is attached to the experiment structure to measure the vibration of the canister and the structure. This sensor will provide background data to determine if any external force causes vibration of the experiment. The location of the accelerometer is not critical; however, since any vibration would be transmitted through the EMP and down the structure, it is probably best to mount it close to the bottom of the experiment.

The other accelerometers are mounted at the top of each inflatable structure. These accelerometers will measure the response and damping to the tube excitation. Size and mass of these accelerometers is more critical due to their effects on the inflatable tubes. Initial investigation has identified accelerometers that are one-half inch cubes and have the required sensitivity. The top tube flange is made so that some or all of the sensors can be mounted inside the flange. The top of the flange is open and space available has a diameter of 1.125 inches and a depth of 0.875 inches. If the excitation system does not fit inside the flange, the accelerometer will.

Figure 4.11 shows the sensor assembly that attaches to the top flange of the inflatable tubes. The accelerometer and excitation device are located in the center

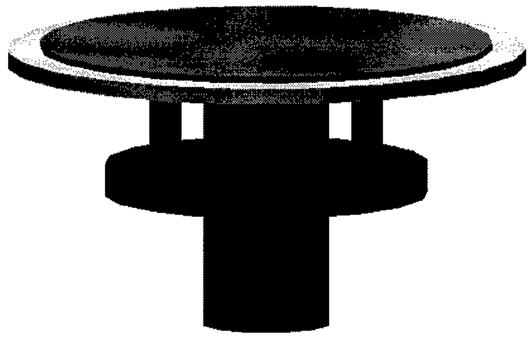

Figure 4.11 Inflatable Structure Sensors

section. The top circle is the target image used for displacement measurement and the bottom flange mounts to the inflatable structure. The goal of the sensor configuration is to minimize the height, in order to maximize tube height. The exact configuration will be determined once components are purchased.

4.6.2 Pressure. The application of the pressure sensors within the design is relatively simple. The environmental pressure sensor is required to monitor the pressure inside the canister. Any commercial sensor that meets the sensitivity requirement is acceptable. The location of the sensor is not critical since the pressure inside the canister should be uniform. The other pressure sensors are each attached to an open end of the inflation system. Size is only a concern in that the sensor must be worked into the inflation system and not interfere with any other components of the experiment.

4.6.3 Temperature. The temperature sensors throughout the experiment also serve two purposes. First, the temperature sensors integrated into the heaters are used to maintain the setpoint temperature for the individual components. However, these integrated sensors do not send data to the computer and therefore sensors are needed to monitor and record the temperature of the critical components. These heaters include the computer, battery box, and digital cameras. Several additional sensors should be included to monitor the overall temperature of the experiment.

The data for these sensors is available for troubleshooting in the event of a failure within the experiment.

The second use of temperature sensors is for the inflation and rigidization processes. Prior to inflation, the structures must be heated above their transition temperature to ensure proper inflation. The computer will periodically check the output of each temperature sensor and determine when the tube is adequately heated. After inflation, the tubes must cool below the transition temperature to complete the rigidization. The computer will again periodically check the sensors to determine when the venting process can begin. Experimentation and testing should be used to determine the minimum number of sensors and their location. In order to achieve useful modal analysis data, the tubes must inflate and rigidize properly.

4.6.4 Force. The force sensors are required to measure the amount of force transferred from the excitation system to the rigidized tubes. The data is needed to analyze the accelerometer data and determine the modal response of the tubes. As stated, the excitation system and its integration into the experiment is being developed outside of the preliminary design. Therefore, the selection and installation of the force gauge is also outside the preliminary design.

4.6.5 Displacement. The length of the inflated and rigidized structures is measured with a digital camera system. The camera system consists of four primary components; the camera, the computer interface card, a light, and the target image. The cameras are each mounted directly above the inflated structures on the under side of the top plate.

A PC/104 digital camera system was selected for its easy integration into the computer,compact size, and high resolution. The camera, shown in Figure 4.12, is essential a CCD array mounted on an electronics card inside a protective case. The camera is connected to a PC/104 imaging card inside the computer. This card both

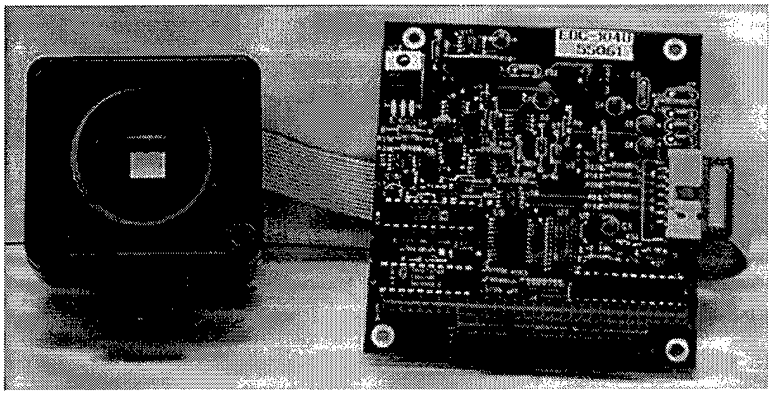

Figure 4.12 Digital Camera and PC/104 Card

controls the camera and transfers the image data into the computer memory. The integration of the imaging card is discussed with the computer assembly.

Due to the dark conditions inside the canister, a light is required to illuminate the target image. There are not specific requirements for the light; however, testing should be conducted to determine the best light color, intensity, and location to enable clear images to be taken. For the initial design, it is assumed that the light is mounted above the inflatable structure, near the camera. The lights will be powered by the same relay that activates the camera.

Another option, for lighting the target image, is mounting light emitting diodes (LED) on the target image. The camera will then photograph the image and LEDs, and the pixel distance between the light sources can be measured. This option has the least complications with regard to reflected light on the CCD array and shadows on the target image.

The target image is the final component to the camera system and it is how the displacement is determined. The basic theory is by using an image of specific size and layout, the number of pixels for any part of the image can be used to determine the distance and angle of the image. By taking several reference images, at distances determined by laser ranging, the distance and angle of the flight image

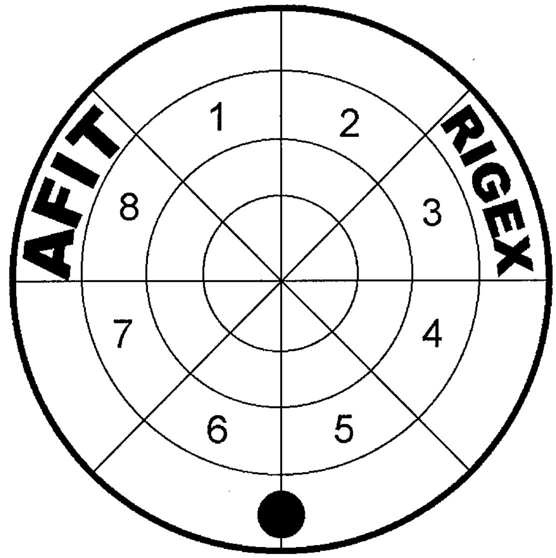

Figure 4.13 Preliminary Target Image

can be calculated to determine the inflated length of the tube. Figure 4.13 shows the preliminary image layout used.

For example, assume the image size is 1000 x 1000 pixels (width by height) and developmental testing shows that at a distance of 5 inches the image is 700 x 700 pixels. If an photo of the image shows it to be 650 x 600 the distance must be greater than 5 inches and the image is tilted. By using several reference points within the image, the actual distance and angle of the target can be calculated.

Preliminary calculations show a possible accuracy of 0.01 inches, which is well within the 1 mm requirement. Two pictures of the target image, at standoff distances of 2.0 inches and 2.1 inches, were compared by aligning a reference point along the left edges of one axis. Then the right edges were magnified until the number of pixels between the right edge could be counted. Using visual reference, the number of pixels between the center of each line was 20; therefore, with a two pixel difference the accuracy would be 0.01 inches.

Comparison of the computer images data will provide more accurate resolution by comparing the slope of the pixel intensity across the axis. With the numerical

data, the peak points of two images can be compared to determine a pixel difference. Additionally, the laser displacement sensors will provide a precise standoff distance for labeling reference images. Finally, by comparing the flight images and the reference images, the actual displacement can be determined.

The critical parts of the displacement measurement are ensuring a quality image and calibrating the reference distance. The image quality is driven primarily by the camera selected and the conditions inside the experiment (lighting, vibration, temperature). The camera requires operating temperatures from 0^o to 70^o C; therefore a heater will be required for each camera. However, these heaters will only be operated prior to and during camera operation.

The video images will also be used to determine if there were any anomalies during the inflation process. However, there is no guaranty that the target image will be visible during the inflation process, since the structure may "flop over" during inflation. Any distance calculations during inflation will be informative, but they are not required at this time.

4.6.6 Voltage. The voltage sensor is not required for the design, however it will be useful in monitoring the total battery voltage during test and evaluation. The voltage data may also be needed in troubleshooting any failures of the experiment during flight. The sensor is placed inline with the main power relay to monitor the total voltage of the battery system.

4.7 Command and Control

With the exception of the three relays controlled by the Space Shuttle crew, all operations of the experiment must be handled internally. The command and control of the experiment is explained in three primary parts; the computer system (hardware), the shuttle relays (initiation), and the event calendar (software).

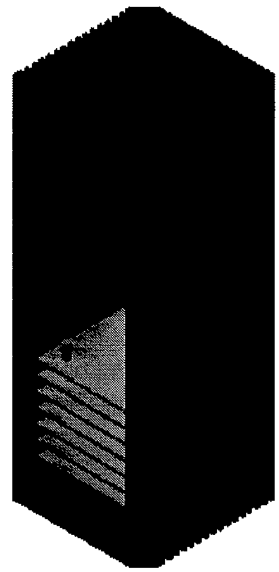

Figure 4.14 PC/104 Computer Assembly

4.7.1 Computer. In the preliminary design review, the decision was approved to use a PC/104 computer system for command and control of the experiment. The following functions should be integrated into the final computer design: central processing unit (CPU), counter/timer, analog input/digital conversion, digital input/output, control relays, power supply, and digital camera interface. Additionally, the Diamond Systems Corporation offers a PC/104 enclosure that provides structural and thermal protection, minimizes vibration, and can be customized to the size of the computer. Figure 4.14 shows a cut-away drawing of the computer cards inside the enclosure.

The CPU card provides the processor and control functions for the computer. As a minimum, a 486 processor operating at 100 MHz should be used. The CPU card also serves as the base card that the other cards are connected to. Differing from traditional computers, the PC/104 architecture has the cards stacked on top of each other with 104 pins providing the connections between each card.

In theory, many cards can be placed in a single stack; however, in application the number of cards stacked above the CPU is limited to five or six. More than six

cards can cause a significant time delay for a signal to pass from the top card to the CPU card. If more cards are needed, a second CPU card, directly networked to the first should be used. Finally, the CPU card will act as the interface between the experiment computer and any outside ground test equipment. An ethernet connection is standard on most PC/104 CPU cards and seems appropriate for this interface.

The counter/timer functions are necessary for implementation of the event calendar (section 4.7.3). For those events that are time driven, a timer is needed to accurately implement the event calendar. Several PC/104 cards were found that offer multiple timers on one card.

The analog and digital input/output functions are necessary for data collection and storage. The input signals are needed to collect all data and information from the system. For digital inputs, the data can be stored directly into memory; whereas analog inputs must be converted into a digital signal for storage. Initial investigations found analog input cards with up to 32 channels and capable of sampling at 200,000 samples per second. The cards also have an analog to digital (A/D) conversion resolution of 16 bits, meaning each analog data point requires 16 bits for storage.

The control relay card provides switching functions for the experiment. One card can contain several relays, where each relay has three connections; open, closed, and common. Assuming the ground is connected to the common and the component is connected to the closed connection, when the relay is switched to the closed position, the circuit is complete and the relay provides a voltage and current to the component. When the relay is switched to the open position, the circuit is broken and no voltage or current is provided. The relay card should be selected to provide the number of relays needed, as well as the necessary voltage and current for each component.

The power supply card receives its input voltage directly from the experiment battery box. Once the command relay is activated, the power supply provides power

to the computer through the PC/104 bus connectors and to external components through output connections. The power supply also acts as a filter and protects the computer from any irregularities in the power supply. The additional outputs for the power supply are driven by the design of the power supply (+5V, +12V, -5V, -12V or a combination). The power supply should be selected to provide the necessary power output and circuitry protection for the computer

The digital camera card is a component specific card that is needed interface the digital camera with the computer. The digital camera connects directly to the card, where the images are routed to the data storage device. Normally one card is needed for each camera in the system. As stated above, the number of cards stacked in a system is limited. Since, each structure will be inflated separately, only one camera will be needed at a time. If the power for each camera is routed through relays, all cameras could be integrated into one board. This integration will require the detailed specifications of the camera and camera board selected for the experiment and should be investigated after the items have been purchased.

Finally, custom built PC/104 cards can be used for specific needs of the experiment. If necessary, these custom cards must integrate into the commercial systems and be tested to ensure all items work together. In addition to the PC/104 computer within the experiment, an external interface will be required to program, test, and download data from the computer. With the wide variety of portable computers and software available, this should not be difficult to accomplish.

4.7.2 Shuttle Relays. The only external control interface between the Space Shuttle and the experiment occurs through three control switches or relays. Each control relay can be switched between "latent" and "hot" by the shuttle crew during the flight, where latent is considered the inactive position and hot is considered active. For safety considerations, one of the relays must be dedicated to shutting off all power from the experiment.

The first relay (Relay A) is dedicated to switching power to the payload through the two power relays. These payload relays, called K1 and K2, are connected directly into the power subsystem of the experiment and act as a failsafe for total shutdown of the experiment. Each power relay is limited to carrying 50V (DC or AC peak-to-peak) at 25A. For this experiment, the baroswitch option is being used. During launch, when the shuttle reaches an altitude of 50,000 feet, the payload support computer will activate Relay A and supply power to the battery system for thermal control. The other two relays are limited to 50V (DC or AC peak-to-peak) at 2A.

The second relay (Relay B) activates the remainder of the experiment. Power is already supplied to the heaters through Relay A, therefore Relay B will initiate power to the computer and start the boot-up sequence. Since the experiment is concerned with measuring the structural performance of rigidized tubes, the test sequence should occur when there is minimum activity and vibration on the shuttle. The best timing for the experiment seems to be during the astronaut rest periods, when there are no major activities or orbital maneuvers. Therefore, it is preferred for Relay B to be activated just prior to the astronauts rest period.

The third relay (Relay C) is still open at this time. In order to obtain the earliest possible flight assignment, the design should minimize the required crew interaction with the experiment. However, as the final design is developed and proposed to NASA, the third relay may be needed to fulfill a control or safety requirement.

In case of emergency, the shuttle crew has the ability to switch all relays for all experiment to latent. If this occurs, the heaters will stop controlling the thermal environment within the experiment and several critical components could be damaged. If the emergency is resolved and the flight activities may resume, Relay A must be switched to hot first to allow critical components to warmup again. After a specified time, the crew can then activate Relay B and begin the experiment again. To prepare the computer for this situation, fail-safe points should be used.

Each time the computer reaches a fail-safe point, it is marked as completed. If the computer is shut-down and then restarted, the operations will resume at the last fail-safe point that was completed. These fail-safe points are programmed into the event calendar.

4.7.3 Event Calendar. Once the computer is assembled and tested, the sequence of events, or event calendar, must be programmed. There are two primary methods of initiating events in the event calendar. A time-based event is begun at a specified time in a sequence. A condition-based event is begun when a predefined set of conditions is met in the experiment. For example, the inflatable structure may require a minimum amount of time to rigidize (time-based), whereas the release of the inflation gas can only occur after the inflatable structure has met a minimum temperature (condition-based).

For the preliminary design, a basic order of events was established with estimated initiating criteria given. Once the developmental and operational testing begins, the event calendar will be refined with additional tasks and more specific criteria. For explanation purposes the event calendar was broken up into logical subroutines (inflation and rigidization, venting, and excitation) that are integrated into the main event calendar.

Each subroutine is run when called by the main event calendar or another subroutine. After the called subroutine is completed the computer resumes with the next event. Table 4.2 is the preliminary main event calendar and Tables 4.3, 4.4, and 4.5 are the preliminary subroutines.

Table 4.2 Main Event Calendar

Event	Description	Condition
1	Activate Environmental Heaters	Relay A = Hot (50,000 ft Altitude)
2	Activate Experiment	Relay B = Hot (Shuttle Crew)
3	Computer Boot-up & Diagnostic	
4	Reset Primary Timer to Zero	$T^* = 0{:}00$
5	Activate Environmental Sensors	T^* = Wait Period
6	Skip to last failsafe point	(In case of unexpected restart)
7	Begin Inflation Process	
7a	Inflation Subroutine (Tube 1)	
7b	Inflation Subroutine (Tube 2)	Tube 1 Inflation Complete
7c	Inflation Subroutine (Tube 3)	Tube 2 Inflation Complete
8	Begin Venting Process	Tube 3 Inflation Complete
8a	Venting Subroutine (Tube 1)	
8b	Venting Subroutine (Tube 2)	Tube 1 Venting Complete
8c	Venting Subroutine (Tube 3)	Tube 2 Venting Complete
9	Begin Excitation Process	Tube 3 Venting Complete
9a	Excitation Subroutine (Tube 1)	
9b	Excitation Subroutine (Tube 2)	Tube 1 Excitation Complete
9c	Excitation Subroutine (Tube 3)	Tube 2 Excitation Complete
10	Deactivate Environmental Sensors	Tube 3 Excitation Complete
11	Mark Final Fail-Safe Point	
12	Shutdown Computer	Final Fail-Safe Complete
13	Relay A = Latent	Shuttle Crew Preparing for Re-entry

Table 4.3 Inflation Subroutine

Event	Description	Condition
701	Reset Timer T1 to Zero	
702	Activate Inflation & Rigidization Sensors	
703	Activate Oven Heaters	
704	Activate Camera Heater	
705	Release Oven Top Pins	Tube Temperature $\geq$ Transition or T1 $\geq$ 30:00 min
706	Activate Vent Solenoid (closed)	
707	Activate Video System (1 image every 10 sec)	Camera Temp $\geq$ Minimum or T1 $\geq$ 30:00
708	Reset Timer T2 to Zero	
709	Activate Inflation Solenoid (open)	
710	Deactivate Video System	T2 = 1:00 min
711	Mark Fail-Safe Point	Inflation Sequence Complete
712	Return to Main Calendar	

Table 4.4 Venting Subroutine

Event	Description	Condition
801	Begin Venting Cycle	Tube Temp $\leq$ Transition-20^o C or T2 $\geq$ 30:00 min
802	Activate Video System (2 images)	
803	Begin Excitation Subroutine	
804	Reset Timer T4 to Zero	Excitation Subroutine Complete
805	Deactivate Inflation Solenoid (closed)	
806	Deactivate Vent Solenoid (open)	
807	Activate Video System (2 images)	T3 = 2:00 min
808	Mark Fail-Safe Point	
809	Deactivate Video System	
810	Deactivate Camera Heater	
811	Deactivate Inflation and Rigidization Sensors	
812	Begin Excitation Subroutine	
813	Return to Main Calendar	Excitation Subroutine Complete

Table 4.5 Excitation Subroutine

Event	Description	Condition
901	Activate Modal Analysis Sensors	
902	Reset Timer T4 to Zero	
903	Activate X-axis Excitation	
904	Deactivate X-axis Excitation	T4 = 0:20 sec
905	Activate Y-axis Excitation	
906	Deactivate Y-axis Excitation	T4 = 0:40 sec
907	Mark Fail-Safe Point	
908	Deactivate Modal Analysis Sensors	
909	Repeat as necessary	
910	Mark Fail-Safe Point	Excitation Subroutine Complete
911	Return to Vent Subroutine or Main Calendar	

4.8 Data Handling

Along with the decision for a PC/104 computer system, PC/104 memory chips were selected for the primary non-volatile memory storage. The disk-on-chip option allows a large volume of data to be stored in a compact, rugged, and permanent form. To determine how much memory is required, an examination of the anticipated data is required. The data is broken up into two categories: sensors and video. Appendix C contains the detailed calculations and assumptions made to calculate preliminary data storage requirements. Table 4.6 summarizes the results of those calculations.

4.8.1 Sensor Data. The sensors discussed earlier can be divided into three categories based on sampling rates; environmental low speed, inflation and rigidization low speed, and structural analysis high speed. The high speed sensors include the acceleration and force gauge sensors sampling at approximately 1024 data points per second, or 1 kilohertz (1 kHz). The low speed sensors include the temperature, pressure, and voltage sensors sampling at 1 data point per second (1 Hz).

Table 4.6 Data Storage Requirements

Sensors	Data Rate	Quantity	Factor	Total
Environmental	$\frac{120 \text{ bytes}}{\text{minute}}$	1	240 minutes	0.03 Mb
Inflation Rigidization	$\frac{14880 \text{ bytes}}{\text{tube} \cdot \text{cycle}}$	3 tubes	1 cycle	0.05 Mb
Modal Analysis	$\frac{0.28 \text{ Mb}}{\text{tube} \cdot \text{cycle}}$	3 tubes	20 cycles	16.8 Mb
Video	$\frac{1 \text{ Mb}}{\text{tube} \cdot \text{image}}$	3 tubes	12 images	36 Mb
			Grand Total	**52.88**

The three situations when data is collected are duration, inflation and rigidization, and modal analysis. The environmental sensors (canister temperature, pressure, and battery voltage) are required for the duration of the experiment. During inflation and rigidization the tube temperature, pressure, and video sensors are used to collect data. Finally, the structural analysis sensors (experiment structure accelerometer, tip accelerometer, and force gauge) are only required while exciting the specific structure.

For low speed data acquisition, there are two subsets of data. The environmental sensors (temperature, canister pressure, and voltage) are scanned at a rate of one data point per second. Therefore if ten channels are required for the environmental sensors, each sensor will have one data point every ten seconds. Since the environment should change relatively slowly, this data sample rate should be sufficient.

The unknown variable in the environmental data is how long the entire experiment will be operational. Assuming the an operational duration of four hours, 28,800 bytes of data are recorded (approximately 0.03 Mb). If there is excess data storage capacity after all experimental data is defined, the environmental data rate may be changed to sample each sensor at one hertz.

The second subset of low speed data is the temperature and pressure sensors for the inflatable structures. For the preliminary design, three temperature and one pressure channel are required for each inflatable structure. These low speed data channels are each recorded at one sample point per second. Assuming a total time of 31 minutes for warming, inflation, and rigidization, 14,880 bytes of data are recorded for each tube. Therefore approximately 0.05 Mb are required for all three tubes.

For high speed data acquisition, three channels are required for the accelerometer attached to the structure. Also, four channels are needed for each inflatable structure, three for the accelerometer and one for the force gauge. This gives a total of 7 channels of high speed data for each tube. Assuming an excitation cycle of 20 seconds per axis, 20 cycles per tube, and 3 tubes, approximately 16.8 Mb of data are required for the modal analysis.

4.8.2 Video Images. The high resolution and large size of each digital image will require a significant amount of memory to store. Appendix C contains the calculations used to determine the memory requirements for each image that is taken.

After discussions with the user, it was determined that approximately six images should be taken over the time of inflation. These images will show any anomalies in the inflation process. Two additional images will be taken after each of the following events to determine the distance and angle of the inflated structures; complete inflation, rigidization, and venting. This gives a total of 12 images per inflatable structure and 36 images for the experiment. Assuming each image is 1 MegaPixel, 36 images will require approximately 36 Mb of data storage.

4.8.3 Data Summary. The amount of data required for each sensor is calculated based upon the sampling rate, number of channels, and length of sampling. Accurate calculations cannot be performed until a detailed and accurate time line

is defined for the duration of each task. However, under the assumed times, a total of 52.88 Mb of storage are required for the video images and all sensor data. This is well below the available capacity of 144 Mb, which will allow the user to expand the duration, number of analysis cycles, and/or video images.

4.9 Heaters

Between the canister integration with the shuttle and the launch, the experiment will not be exposed to extreme temperatures. However, after launch and the opening of the payload doors, the experiment may cool very rapidly. Several of the components, including the computer and digital cameras, will not operate at temperatures below 0^o C. Additionally, the performance of the batteries declines rapidly below 0^o C. Therefore, heaters must be used to maintain a minimal temperature for these components.

After discussions with past GAS experimenters and a review of commercial products, *MINCO Products, Inc.* heaters were chosen for the experiment. MINCO offers many thermofoil heaters in a variety of sizes and power outputs. Kapton heaters were selected for their low outgassing and flexibility in location and installation. In the case of the ovens, the heaters will be powered and left on until the tubes are adequately heated. However, the remainder of the heaters will require monitoring to regulate the temperature of the components.

In addition to the heater elements, MINCO offers temperature controllers for their heaters. The controllers uses DC power supply and a resistance sensor to monitor the temperature of the heater. If the temperature is below the setpoint of the controller (preset from factory), the heater element is powered until the setpoint is reached, at which point the circuit is broken and the power is turned off. The heaters are placed directly onto the component which is to be heated. Figure 4.15 shows one Thermofoil heating pad and autonomous control units.

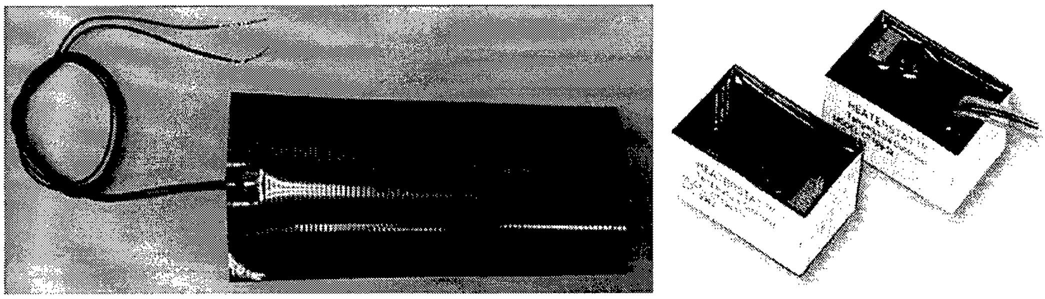

Figure 4.15 MINCO Thermofoil Heater and Control Unit

MINCO offers a variety of installation options for the Thermofoil heaters. The film adhesive methods is best for outgassing and the temperature ranges of the canister. There are two options for integrating the heaters and controllers into the experiment. First, a separate module may be used to house all of the controllers in one enclosure. The second option is mounting the controllers on a PC/104 card and placing them inside the computer box.

The controller card would not be connected to the computer, it would be stacked above the computer on blank cards and then wired to a connector. This would simplify the connections to the structure and protect the controllers. Additionally, any heat generated by the controllers would warm the computer and save battery power. Also, to control some of the heaters (ovens and cameras), they may require wiring through the relay card of the computer.

The configuration shown in Figure 4.16 has several controllers mounted to a blank PC/104 card. The connections are soldered to a screw terminal strip that will allow easy connections to the battery cells and heaters. The number of cards is driven by the number of heaters and controllers required for the experiment.

The preliminary design of each major subsystem in the system architecture has been described. These subsystems include the experiment structure, the inflatable tubes, inflation and rigidization, power, sensors, command and control, data handling, and heater systems. In addition to this hardware, preliminary power, weight, and cost analyses are performed for the entire system.

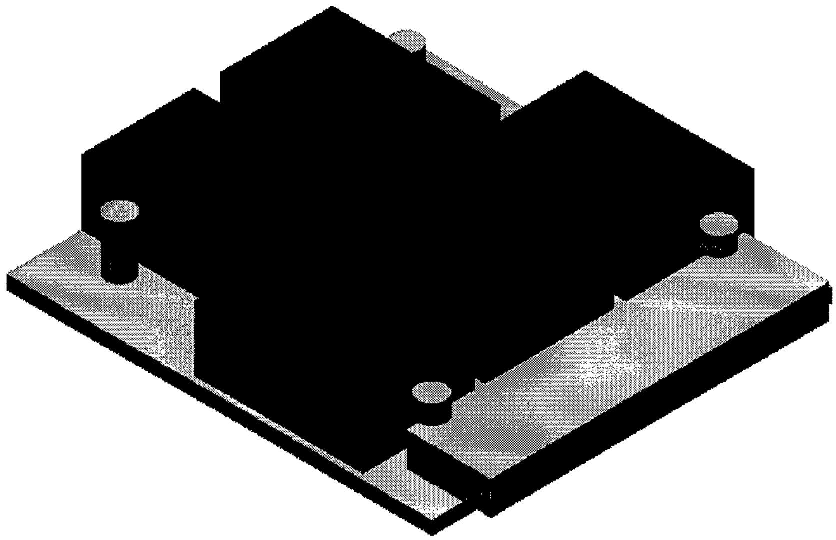

Figure 4.16 Heater Controller Cards

4.10 Power Analysis

The total power available is limited by the voltage and current flow through the power relays. The main relay has two lines rated at 1,250 Watts (50V at 25A) and the two additional relays are rated at 100 Watts each (50V at 2A). This gives a practical limit of 2700 Watts; however it is clear that the battery system cannot provide that much power. Therefore, the limiting factors on available power are size and weight.

In order to provide a baseline power budget, a power analysis of the system is required. To calculate the power draw of each component, the operational voltage and current were required. Some of this data is available from manufacturer specifications; however, much of the data must be determined by measuring the individual components.

The second aspect of power analysis is calculating the lifetime of the batteries. Each D-cell Alkaline battery has an approximate lifetime of 17 Amp-hours, that is if the component is drawing one amp of current, it will operate for 17 hours on one battery cell. The duration of equipment use was used to calculate the expected draw

on the components and accurately size the battery system. The power distribution can be divided into two groups; the computer and the heaters.

The computer will power its individual components and all of the sensors. The DC/DC power supply in the computer requires a 28V input. The amount of current required is driven by the type and number of components used in the experiment. Assuming a maximum current draw of 5A and an operational time line of three hours, one battery cell can power the computer and sensors for the duration of the experiment. If more current is needed, either in draw or lifetime, two battery cells connected in parallel are required.

The heaters are expected to require the majority of the power for the experiment. However, until developmental testing is completed, the voltage and current requirements cannot be determined. The environmental heaters operate at a low temperature (0^o C) from launch until experimentation is complete. The oven heaters operate at a much higher temperature (150^o C) but for a shorter time frame.

By examining GAS experiments with similar functions and complexity, the use of eight battery cells at 30V each should be sufficient. Given the largest driver on the battery system is the power draw from the heaters, the number and temperature required for the heaters should be minimized. There are two options for limiting the heater power. By limiting the flight parameters for shuttle assignment, the lowest environmental temperature for the canister can be limited. Similarly, accurate data on canister temperatures could reduce the transition temperature of the inflatables, and therefore lower the oven temperature and power requirements.

Two additional aspects that determine the available power and lifetime are depth of discharge and temperature effects. As the batteries are discharged, the voltage may begin to decrease. Although alkaline batteries should provide an acceptable discharge, testing is required to determine what level of discharge should be accounted for in the design. With regard to temperature, the performance of the batteries will decrease with temperature. Again, testing should be performed to

determine the best temperature setpoint for the heater or heaters inside the battery box. All of these factors will effect the power allocation and analysis. Although a detailed power analysis is not feasible at this time, initial weight and cost analyses can be performed on the preliminary design.

4.11 Weight Analysis

The maximum allowable weight for a GAS experiment is 200 pounds. In order to determine that the preliminary design is within the weight requirements, a basic weight analysis was done. The weight each element in the work breakdown structure was determined, and then all elements were summed to determine the total weight. For most parts, an estimated weight was determined from manufacturer specifications of a typical part. For the components on the design that are custom made, the volume and density of the material were determined and then the weight calculated. The data and methodology for the weight analysis is listed in Appendix D and summarized in Table 4.7.

The total estimated weight is 191.62 lbs. The cabling and connections were estimated to be five percent of the total design. This leaves 4 percent of the maximum allowable weight available in case of any modifications or increases in the design. Although this weight estimate does not offer much room growth, it should be noted that the "worst-case" conditions were assumed for many of the components. Once the specific components are received, a more detailed weight and balance analysis can be performed.

As the design matures, the weight of the experiment may increase and there are several options for lowering the total weight. As the numbers show in the weight analysis table, the two assemblies which offer the greatest potential weight savings are the structure and the power system. The weight of the structure was calculated base on a given thickness and a relatively high density aluminum. If the thickness of any fabricated components is reduced, the total weight of the structure will decrease.

Table 4.7 Weight Analysis

Item	Method	Weight (lbs)	Quantity	Total
Structure	C	58.24	1	58.24
Battery Cell	W, C	6.60	8	52.80
Battery Box	C	18.60	1	18.60
Computer	D, W	7.75	1	7.75
Sensors	D, E	2.48	–	2.48
Heaters	D	1.00	5	5.00
Oven	C	4.25	3	12.75
Inflatables	C, D	2.50	3	7.50
Inflation System	W, E	5.25	3	15.75
Video	D, E	0.75	3	0.75
Wiring	E	10	–	10
			Grand Total	**191.62**

Method Abbreviations

D = Company Data E = Estimate C= Calculate

Likewise, the use of a lower density aluminum, or a lower density material, would also decrease the total weight. While considering both of the these options, the overall structural integrity of the experiment must be maintained.

Additionally, the power system is intentionally over designed to allow the final design more flexibility. The battery box may not be required if NASA agrees to allowing the batteries to vent through the canister vent port. This would remove over 18 pounds from the design. As discussed earlier in the power analysis, the total power required cannot be determined until the design is finalized. If fewer battery cells are required for operation, the weight of the system may reduce significantly.

4.12 Cost Analysis

In addition to the weight and power analysis, a preliminary cost analysis was done to determine the cost of the flight hardware and initial ground test equipment. As with the weight analysis, the cost was broken down for each element of the

Table 4.8 Cost Analysis

Item	Method	Cost ($FY00)	Quantity	Total
Structure	E	675	1	675
Battery Cell	D	25	8	200
Battery Box	E	350	1	350
Computer	D	2650	1	2650
Sensors	D, E	7650	–	7650
Heaters	D	150	5	750
Oven	E	700	3	2100
Inflatable / Flanges	D,E	600	3	1800
Inflation System	D,E	785	3	2355
Video	D	1650	3	1650
Wiring	E	500	–	500
Test Equipment	E	8450	–	8450
			Grand Total	**$29,130**

Method Abbreviations

D = Company Data E=Estimate

work breakdown structure and summed for the total cost. The methodology used in determining the cost of each assembly, as well as the component costs, are discussed in Appendix D. The results of the cost analysis are summarized in Table 4.8, for a total of approximately $29,130.

In addition to the flight hardware, components and assemblies are required for developmental testing. The estimated cost of the test hardware is equivalent to the flight hardware (approximately $20,000). Therefore, the grand total for test hardware, test equipment, and flight hardware is approximately $50,000. The remainder of the $200,000 budget is available for the services, equipment, and facilities for safety certification and qualification of the experiment.

V. Recommendations

5.1 Design Conclusion

This preliminary design is by no means an exhaustive explanation of every detail of the design. It is a starting block to which the next phase will build on and modify, within the scope of the users objectives and requirements. The preliminary design provides a first look at each element of the system architecture and chooses the best available alternative from a total system perspective.

The size, layout, and connections of many components will be determined once all components are available. Commercial components can vary greatly by manufacturer and model. The details of their integration and assembly will be determined once the components are purchased and received. For custom parts that must be manufactured, Appendix E contains a drawing of each component with some preliminary dimension and assembly information.

The two areas of the design which required the most additional work are computer and power requirements. The assembly of the computer, wiring, and programming will require a considerable knowledge of computer systems. Additionally, an interface computer must be configured to upload programming and information and download data, as well as for safety checks of the fail-safes.

As stated in the power analysis, a detailed analysis must be performed after developmental testing of individual components is completed. Many aspects of the design are time driven, meaning the longer the total experiment is active, the more resources are needed. This is especially true for power consumption and data collection. After experimentation has determined the required warming and cooling time for each inflatable structures, a detailed time analysis will provide a baseline for power requirements.

5.2 *Test and Evaluation*

During the preliminary design and component selection, testing was limited to available results from manufacturers and government agencies. Since very little hardware was available for the design, testing could not be performed. The primary interests in the data which was available, was survivability and operational conditions in space. For example, accelerometers can be very sensitive to shock, therefore any accelerometer selected had to withstand the vibrations of launch. With regard to operational conditions, the pressure and thermal operating range of each component was determined and compared to the typical environment experienced by GAS experiments. Whenever possible, within cost and performance requirements, flight qualified components (as determined by the manufacturers and/or NASA) were used within the design.

Testing of the actual experiment hardware should be divided into two categories: developmental and operational testing. Developmental testing focuses on each component and/or subsystem to ensure the equipment performs as expected. With regard to developmental testing, the following subsystems should be tested individually to determine performance and verify compliance with component requirements; sensors, computer, heaters, inflatable structures, inflation system, excitation system, and digital imaging.

All sensors need to be tested for accuracy and sensitivity to ensure collection of accurate data. The computer should be assembled and programmed to verify component interaction, data collection, program execution, and the external interface. Also, the inflation systems should be tested to ensure adequate pressures and airtight connections.

The inflatable structures will require substantial testing to verify transition temperature, packaging, and structural response after rigidization. The excitation system can be tested in controlled environment to measure the excitation and vibration data of the structure. Lastly, the digital camera system must be tested

and calibrated to ensure accurate distance measurements at multiple points. A non-contact displacement sensor, such as the laser triangulation systems discussed earlier, can be used to calibrate the video system and validate the distance calculations.

In addition to individual component testing, several subsystems can be tested prior to complete assembly of the experiment. For example, a inflatable structure can be warmed, inflated, rigidized and excited inside a vacuum chamber to simulate part of the space environment. This testing could be performed as an independent subsystem from the structure, power, and computer of the experiment. Also, the oven heaters and packaged tubes will require testing to determine heating times, temperature, and power levels.

Operational testing focuses on testing the entire system as a whole. The primary goal of operational testing is to verify the systems will operate as designed under operational conditions. To simulate the effects of launch and orbital insertion, the system is mounted to a shaker table, which simulates the shocks and vibrations of a shuttle launch. To simulate the conditions of space, the system is operated in a thermal vacuum chamber. Running the entire event calendar in a controlled environment will verify the system works from beginning to end. Also, the thermal-vacuum testing should very the temperature of the environment across the spectrum of possible flight temperatures, specifically the minimum and maximum GAS canister temperatures (-160^o C and +100^o C).

Recall the primary objective of the experiment is to validate *ground* testing of space inflatable structures. The data collected from running the system in operational testing (1-g) will be compared to the performance on-orbit (0-g). The results of the data analysis can then be used to validate ground testing and orbital inflation/rigidization.

5.3 Operations and Support

After all test and evaluation are complete, the experiment should be ready for transition to NASA. The flight process is divided into three segments, pre-flight, flight, and post-flight. Each of theses process is briefly discussed below.

5.3.1 Pre-Flight Activities. After the Phase III SDP is submitted, NASA will provide a shipping EMP and container that match the GAS canister components. This ensures that the experiment will fit inside the flight canister. If the battery vent is required, the shipping plate will also include the necessary fittings to ensure the connections are correct. After the final design has been given safety approval, the experiment must be sent to Kennedy Space Center (KSC) approximately three months before the assigned shuttle flight.

Approximately two months before the flight, an integration team must go to KSC to assist with the testing and installation of the experiment into the flight canister. The number of individuals is limited and the experiment should be in a condition such that no more than three days are required for the final inspection and integration. During the integration, the team must demonstrate that the built-in failsafe operations work. The experiment should be capable of storage for at least four months, since shuttle flights are sometimes delayed.

During the integration, the battery box should be sealed and purged with nitrogen, each inflation system should be charged to the appropriate pressure, the flight computer should be checked for proper operation, and all cables and connections should be double checked. After the canister is sealed and leak tested, it will be purged with dry nitrogen gas at one atmosphere. The canister will remain in this configuration through storage, installation into the shuttle cargo bay, and pre-launch activities.

5.3.2 Flight Activities. If the shuttle flight and the experiment operations go as planned, the only activities required are initiating the experiment through Relay B and powering down the experiment prior to landing. However, if something unexpected requires the shuttle crew to power down the experiment (or all experiments) during operation, a contingency must be planned.

If the experiment is without power for an extended time, the temperature of critical components may drop below acceptable levels. Therefore the first step in a re-start of the experiment is switching Relay A on and powering the environmental heaters. After a specified time, Relay B is switched on to re-boot the computer are re-start the event calendar. At that point, the computer should recognize the discontinuity and begin operations from the last programmed fail-safe point.

The worst case scenario is power loss during the time the structures are inflated but not yet rigidized. This could cause the structure to deflate and rigidize in an odd shape which the heaters could not re-warm. For this reason, the inflation and rigidization sequence is staggered for each tube. Given the general predictability of shuttle operations, it is highly unlikely of a critical power loss during all three inflation and rigidization processes.

After the computer has completed all activities in the event calendar, it will go into a shutdown sequence to prepare for re-entry and landing. Prior to re-entry, the shuttle crew will deactivate all GAS experiments in preparation for landing. During re-entry, the canister will pressurize through the valve in the EMP. Additionally, the vent valve for the structures are open without power, allowing the structures to maintain an equilibrium with the canister and increasing the probability of landing undamaged.

5.3.3 Post Flight Activities. After the GAS canister has been removed from the shuttle, the integration team will return to KSC to participate in the removal of the experiment. The first task is to determine the canister properly vented and

returned to one atmosphere. If this did not occur, the team should slowly open the vent valve to allow a controlled pressurization of the canister.

To maintain data integrity, a computer download is the first activity that should be done after the IEP is removed. By connecting the ground support computer to the experiment computer, all data can be transferred and copied. After the download is verified, the experiment will be removed from the canister. At this point the inflatable structures should be removed and packaged separately. The data and tubes will be returned to the user for analysis and additional testing to determine if space rigidization had any unexpected effects on the structure. The remainder of the experiment can be taken by the integration team or shipped by KSC.

5.4 Systems Engineering Evaluation

One of the secondary objectives of the project was to "implement systems engineering principles into the experiment's design." After evaluating several systems engineering processes, the NASA process was selected. This sections will describe how the process was implemented and evaluate how well the preliminary design met the criteria. To reiterate, the NASA SEP is shown in Table 5.1

5.4.1 Recognize Need or Opportunity. Step one of the process was completed by the sponsor and the user. In addition to recognizing the need for validating ground testing of rigidized structures, the sponsor was able to secure a GAS reservation for the experiment. In a pure systems engineering process, the decision for how to conduct the experiment would be part of the creating alternative design concepts and then selecting one concept. However, since the GAS canister was one of the requirements, it was the method implemented.

The work of this thesis focussed on steps two through five. The first activity examined was determining the user's needs. Without a clear definition of the need from step one, there is no guaranty that the final system will achieve the users

Table 5.1 NASA Systems Engineering Process

Step	Description
1.	Recognize Need/Opportunity
2.	Identify and Quantify Goals
3.	Create Alternative Design Concepts
4.	Do Trade Studies
5.	Select Concept
6.	Increase the Resolution of the Design
7.	Perform the Mission

expectations and goals. Therefore, step two involved defining a mission statement, objectives, requirements, and constraints (Sections 1.4-1.7).

5.4.2 Identify and Quantify Goals. Recall from Chapter 1, the goals were defined as the mission statement, objectives, and requirements. Upon examination, the preliminary design appears to meet the mission statement and objectives. A viable system has been designed to collect data on space rigidized structures, those structures will return to Earth aboard the Space Shuttle for further laboratory testing, and systems engineering was implemented into the design. With regard to enabling the application of rigidized structures to operational systems, the completion of a successful flight, analysis of data, and acceptance by the space community will determine if that objective and the mission statement are achieved.

When comparing the requirements and constraints to the preliminary design, the following items are apparent. For the operational requirements, the data requirement for position, modal analysis, and post-flight data are met. However, the preliminary design only incorporates one storage, deployment, and rigidization method. This decision was made for several reasons, primarily data validation, complexity, and the constraints.

In order to maximize confidence in the data, several data sets must be taken on one design. If a single experiment is conducted, it is not possible to tell if the results

are typical or an anomaly. Therefore, by implementing one packaging, inflation, and rigidization method, the three data sets can be compared and the validity of the data can be verified. With regard to complexity, the more complex the design, the more opportunities for mission critical failures. The experience from past GAS experiments emphasize that simple designs have a greater success rate than multi-role experiments. Finally, the constraints of the system limit the size, weight, and cost of the system. The limiting factor of size allows very little room for large and complicated experiments. By using one configuration, the preliminary design offers better data, increase probability of success, and fits within the constraints.

With regard to the functional requirements, the preliminary design meets all categories. The majority of the experiment uses commercially available components and many of these critical components (including computer, heaters, and sensors) are flight qualified. The only component of the experiment that is time sensitive are the batteries, which can withstand the four month storage limit. As far as on-orbit lifetime, an analysis will have to be done to determine how long the experiment can stay inactive after launch before the environmental heaters used too much battery power.

During the preliminary design, every effort has been made to select components that have a high reliability and will survive the Space Shuttle environment (including launch loads, orbital temperatures, and reentry). The battery system provides all required power to the experiment and the computer performs all autonomous control once activated and stores the collected data for post-flight analysis.

When comparing the preliminary design to the project constraints, the experiment meets all the limits. Using this preliminary design as a starting point, the remainder of the project should be completed within the two year time frame. After the goals were identified in the mission statement and objectives, and quantified in the requirements and constraints; the next step in the systems engineering process is to develop design concepts.

5.4.3 Create Alternative Design Concepts. This step in the process is intended to develop several distinctly different ways of achieving the goals in step two. However, as stated above, the user has already determined the primary design concept: a Get-Away-Special experiment. Therefore, this step was taken to the next level and applied to the major subsystems in the experiment. Chapter 3 examined the requirements and options for each subsystem.

For example, the displacement data could be gathered using two different sensors: laser measurement or digital camera. The laser measurement option generated a laser, which reflected off the top of the inflated structure and calculated a distance accurate to within micrometers. The digital camera used an optical image place on the top of the inflatable structure and post flight analysis to determine the height and angle of the image. To determine which system was preferred, a comparison (trade study) was performed.

5.4.4 Do Trade Studies. Since alternative concepts were examined for each subsystem, a trade study was necessary to determine which of the options best met the experiment goals. When considering which option is "best", there were several criteria to consider. In addition to the specific characteristics of the option, the integration into the total experiment had to be evaluated. In general, decision were based upon which option produced the best data, while minimizing the volume, weight and power required.

Using the example of the displacement sensor, the laser system would produce better data (without extraneous analysis); however, it required much more power to operate and weighed considerably more that the video system. Additionally, the user desired video or digital images of the inflation process, so the digital camera option met that capability as well. After comparing the benefits and drawbacks of all the options, a decision was made on the method for each subsystem.

5.4.5 Select Concepts. After investigating and designing alternative concepts and comparing them with a total system perspective, one concept is selected for use in the system. The decisions made in the design are outlined in Tables 3.1 and 3.2. These decisions were presented to the user at a preliminary design review. Although some aspects of the design would be driven by component selection and integration, the decisions on many subsystem alternatives were presented. Upon agreement by the review committee, the details of component integration and the preliminary design could begin.

5.4.6 Increase Resolution of the Design. The component integration and preliminary system design are the focus of Chapter 4. This thesis has performed several iterations on the preliminary design, increasing the resolution and detail of the experiment. As additional iterations are completed, the final flight design will emerge. It is probable that once components are purchased and received, the design will be modified to integrate the specific characteristics of each component. However, the methodology, assumptions, and decision making included in this thesis should provide a framework that the design can work within and minimize the amount of additional work that must be done.

5.4.7 Perform the Mission. The final step, perform the mission, remains for the completion of the systems engineering process. Once again, this is not a step-by-step process that progresses until completion; it is an iterative process that continues to evaluate new decisions based upon the needs, goals, design concepts, trade studies and current design. As developmental testing begins and the design of the experiment is finalized, the focus should continue to be upon meeting the objectives, requirements, and constraints set forth at the beginning of the project and the systems engineering process.

Once the RIGEX experiment is successfully flown and operated aboard a shuttle flight, the data analysis will be performed. This analysis is a critical step in

validating ground test and evaluation methods for inflatable, rigidized structures. The successful validation of ground testing will allow manufacturers to build larger and more complicated rigidized space structures with confidence that they will perform as designed. Finally, the successful application of rigidized inflatable structures will help the United States Air Force to continue meeting its goal of space superiority.

Appendix A. Payload Accommodations Requirement

The PAR is divided into six sections: introduction, payload description, standard services, optional services, technical support services, and schedule. NASA provides a "boilerplate" that includes many of the sections verbatim in the document, as well as optional statements for many of the the sections.

The introduction is a NASA section that describes the PAR document and defines the customer role in the process. The payload description should include the size and weight of the payload, a description of the experiment goals, a hardware description of each primary subsystem, and an operational scenario for the payload.

The standard services section details the basic services that are provided for a GAS experiment. These services include the container accommodation (atmosphere, insulation, and venting), the flight operations (flight parameters, activities, payload control and malfunctions), the ground operations (storage and handling, final preparation, and leak tests), safety (preliminary analysis and hazard descriptions), and post flight data. The optional services allow the experimenter to add options to the experiment at a greater cost. The technical support services are any test and analysis support requested from NASA (vibration, EMI, vacuum, etc.).

Finally, the schedule communicates the earliest acceptable launch data and the preliminary dates that the experimenter expects to complete the various milestones of the documentation process. This attachment includes the draft Payload Accommodations Requirement (PAR) required by NASA.

NASA SMALL SELF-CONTAINED PAYLOAD PROGRAM

GET AWAY SPECIAL

G-0321

PAYLOAD ACCOMMODATIONS REQUIREMENTS

____
Date

Payload Approval:

____
Payload Manager

Date______________________________

Maj. Greg Agnes
Customer Contact

Date______________________________

____
Organization

Air Force Institute of Technology
(AFIT/ENY)

GSFC Approval:

____
Technical Manager

Date______________________________

____
GAS Mission Manager

Date______________________________

NASA SMALL SELF-CONTAINED PAYLOAD (SSCP) PROGRAM

GET AWAY SPECIAL (GAS)

G-0321

PAYLOAD ACCOMMODATIONS REQUIREMENTS (PAR)

1.0 INTRODUCTION

This accommodation plan defines the technical agreement between NASA/Goddard Space Flight Center (GSFC) and the GAS Customer concerning the unique information needed for the preparation, flight, and disposition of this GAS payload. The general plans for handling of GAS payloads are described in the GAS Experimenter Handbook and the Payload Integration Plan (PIP) -- Space Transportation System and Get Away Special Carrier (NSTS-44000).

Appropriate information from this accommodation plan will be used for a GAS payload unique PIP to the GAS Carrier/STS PIP and its associated annexes.

By signing this PAR, the Customer Contact and Payload Manager hereby certify that this payload and none of its components as flown on the Shuttle shall be sold, donated, or otherwise transferred for use as a commemorative item or work of art.

2.0 PAYLOAD DESCRIPTION

2.1 Size and Weight

The experiment is contained in the 5.0 ft^3 canister and has a maximum weight of 200 pounds.

2.2 Experiment Description(s)

The purpose of the experiment is to collect data on the inflation, rigidization, and modal analysis of several rigidized inflatable tubes.

2.3 Device Description(s)

The experiment can be divided into seven subsystems: structure, power, inflatable tubes, inflation & rigidization, excitation, command and control, and sensors. The preliminary design and layout of the components and subsystems is shown in Figure 2.3-1.

The structure is made primarily of 1/4 inch aluminum that is welded at the joints. The top plate has a bolt pattern and opening for vent tubing that matches the EMP. Four lateral support bumpers are attached to the underside of the bottom plate, to allow for adjustment during the canister integration.

The center area of the structure houses the power subsystem and battery box. The battery box is made of 1/8 inch aluminum and is sealed with a viton o-ring when the top is attached. The power system consists of eight 30V DC cells, each comprised of 20 D-size alkaline batteries. The eight battery cells are diode isolated and wired through Relay A on the GCD.

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PostScript printer, but not to
other types of printers.

Fig 2.3-1 RIGEX Assembly

The height of the structure is divided into four equal wedge-shaped sections. Three of the sections are used for the inflatable structure assemblies. The inflatable tubes are 22 inch long and 1.375 inch diameter tubes that are flattened and accordion folded for packaging. The tubes are connected to the experiment by a flange which connects to the bottom plate. The top flange on the tube is cantilever and contains an excitation system and sensors.

The packaged tubes are stored in a thermoplastic oven, which is held closed by two retractable pins. Prior to inflation, the tube is warmed above the transition temperature by heating pads in the oven. Once the temperature reaches an adequate level, the tubes are pliable and ready for inflation.

The inflation system provides for a controlled pressurization of the tubes. A pressure cylinder releases nitrogen gas through a solenoid and pressure reducing valve to maintain 4 psia inside the tube. As the nitrogen expands inside the warmed tube, a relief valve regulates the pressure. After inflation, the tube begins to cool until it reaches an equilibrium with the canister. Once the tube has cooled below the transition temperature, it has rigidized and the inflation gas is vented.

To test the structural response of the rigidized tubes, a modal analysis is performed. A piezoelectric excitation device causes an arbitrary vibration in the tubes, which is monitored by an accelerometer.

The command and control of the experiment is performed by a PC/104 computer system. The computer executes an event calendar once it is activated by Relay B. All sensor data is collected by the computer during operation.

The sensors used in the experiment are divided into four categories: environmental, inflation and rigidization, modal analysis, and video. The environmental sensors collect data on the temperature of several components, the pressure inside the canister, and the voltage of the power system. The inflation and rigidization sensors collect temperature and pressure data on the inflatable tubes. The modal analysis sensors used tri-axial accelerometers on the tubes and the experiment stucture, as well as a force gauge. Finally, a digital video system is used to monitor the inflation and rigidization process.

2.4 Operational Scenario

After launch, the experiment is designed to use the baroswitch option to activate Relay A and provide power to the environmental heaters. These heaters maintain the temperature of critical components above 0° C during the flight. The filtered relief valve is used to vent the canister during ascent and repressurizes during reentry and landing.

When Relay B is activated, the computer proceeds with control, operations, and data collection until either the event calendar is completed or the experiment is deactivated. During this time, the environmental sensors collect data on the canister temperature and pressure, as well as the battery voltage.

As the inflation and rigidization process is begun, heaters warm the inflatable above its transition temperature. Once warmed, nitrogen gas slowly inflates the structure, while the video sensors record the inflation. After inflation, the structure will radiate and cool until an equilibrium temperature is achieved. After the rigidization is complete, the inflation gas is vented. During the entire process, temperature, pressure, and displacement sensors will collect data.

To test the structural properties of the rigidized structure, an excitation device is placed at the cantilever end of the inflatable tube to cause vibration. During each excitation cycle, the accelerometers collect data on the modal response of the inflatable structures. Once all activities in the event calendar are complete, the computer will enter an inactive state until power is disconnected for reentry.

3.0 STANDARD SERVICES

3.1 Container Accommodations

3.1.1 Internal Atmosphere

The container will be purged with *Dry Nitrogen* and sealed at one atmosphere pressure prior to installation into the Orbiter.

AND

The container will incorporate a filtered relief valve so that it will evacuate during ascent to orbit and will repressurize during reentry and landing.

3.1.2 Insulated End Plate Cover

An insulated end plate cover with a silverized Teflon exterior coating will be installed over the container Experiment Mounting Plate (EMP) exterior.

3.1.3 Battery Box Venting

The battery box in this payload will be vented through the upper end plate via two 15 psid pressure relief valves.

3.1.4 Baroswitch

The GAS Control Decoder (GCD) altitude switch *will* be used to turn on Relay A.

3.2 Flight Operations

3.2.1 Flight Design

NASA will identify a Shuttle flight opportunity appropriate to the following payload requirements and within the constraints of the SSCP queue.

Orbit:	**Altitude**	*No requirement*
	Inclination	*No requirement*
Orientation:		*No requirement*
Stabilization:		*No requirement*
Other:		*No requirement*

All of the above requirements that cannot be accomplished by NASA within the established plans for the identified flight will be accomplished as optional services delineated in section 4 of this document.

3.2.2 Flight Activity

The assignment of GAS Control Decoder (GCD) relay states to specific payload functions is shown in Table 3.2.2-1. The required payload crew activities during the flight are shown in Table 3.2.2-2. All relay operations beyond the first six (6) will be delineated as *optional services* in section 4 of this document.

RELAY	STATE	PAYLOAD FUNCTIONS
A	By Baroswitch HOT (H)	Power provided to environmental heaters, which maintain minimum temperature of critical components within the experiment.
	LATENT (L)	All power removed from the experiment.
B	HOT (H)	Power provided to experiment computer. Computer remains active until event-calendar complete or power removed.
	LATENT (L)	Removes power supply to the computer.
C	HOT (H)	Not used at this time
	LATENT (L)	Not used at this time

TABLE 3.2.2-1 PAYLOAD CONTROL FUNCTIONS FOR G-0321

RELAY OPERATION SEQUENCE	GCD RELAY (A, B, OR C)	STATE (TO H OR TO L)	MISSION CONDITIONS AND CONSTRAINTS
01	A	To Hot	Baroswitch at 50,000 feet
02	B	To Hot	At start of minimum 'g' period. Less than 0.01 g's during operation.
03	B	To Latent	Approximately 6 hours after 02
04	A	To Latent	Prior to shuttle re-entry
05			
06			

TABLE 3.2.2-2 PAYLOAD OPERATIONS PLAN FOR G-0321

FOR A NOMINAL DURATION MISSION, THE MINIMUM ACCEPTABLE OPERATING TIME FOR THIS PAYLOAD IS *4 HOURS*.

IN THE EVENT OF AN ON-ORBIT ANOMALY, THAT RESULTS IN A SHORTENED DURATION MISSION, THE MINIMUM OPERATING TIME FOR THIS PAYLOAD IS *2 HOURS*. IF THIS TIME IS NOT ACHIEVABLE, THIS PAYLOAD WILL NOT BE ACTIVATED/WILL BE DEACTIVATED AS SOON AS POSSIBLE.

ALL GCD RELAYS WILL BE IN LATENT STATE AT LAUNCH

3.2.3 Payload Power Contactor (PPC) Malfunction Inputs

PPC Malfunction inputs will not be used.

3.3 Ground Operations Requirements

3.3.1 Storage, Handling, and Integration of Customer Hardware

PREFERRED INTEGRATION SITE:

Kennedy Space Center

MAXIMUM AND MINIMUM ALLOWED STORAGE TEMPERATURES:

30 deg C / 10 deg C

MAXIMUM AND MINIMUM ALLOWED RELATIVE HUMIDITY:

70% / 30%

CLEANLINESS REQUIREMENTS FOR PAYLOAD INTEGRATION:

Class 100,000 Clean Room

REQUIREMENTS FOR GASES OR LIQUIDS:

Nitrogen Gas for Pressurized Cylinders

SPECIAL REQUIREMENTS FOR CUSTOMER HARDWARE HANDLING:

None

3.3.2 Payload Final Preparation

The customer plans to install the following items into his payload just prior to payload installation into the GAS flight container:

Battery Cells, Inflatable Tubes, Pressurized Gas (into storage cylinders)

3.3.3 Leak Test Levels

After payload installation, the container *will not* be pressurized for the purpose of leak testing. Pressurization of no more than 10 psig for no more than 20 hours will be permitted by the customer.

3.4 Safety

3.4.1 Inspection

Assemblies that cannot be opened and examined during safety inspection at the launch site must be sent to NASA for inspection and sealing prior to shipment of the payload. These assemblies will not be further opened by the customer prior to flight. The following assemblies fit this category *(if none, write* none*)*:

None

3.4.2 Preliminary Hazard Analysis

Figure 3.4.2-1 is the completed Payload Safety Matrix resulting from a preliminary hazard analysis on this payload. Figure 3.4.2-2 is the associated Hazard List for this payload.

GAS PAYLOAD SAFETY MATRIX – FLIGHT OPERATIONS			
PAYLOAD G-0321	PAYLOAD ORGANZATION *Air Force Institute of Technology*	DATE *mm/dd/yy*	PAGE *1*

SUBSYSTEM	HAZARD CATEGORY: Collision	Contamination	Corrosion	Electrical Shock	Explosion	Fire	Temperature Extremes	Radiation
Inflation	X							
Rigidization								
Excitation								
Electrical				X				
Environmental Heaters							X	
Pressure Systems					X			
Materials								
Mechanical								
Structure	X							

FIGURE 3.4.2-1 - FLIGHT OPERATIONS

GAS PAYLOAD SAFETY MATRIX – GROUND OPERATIONS

PAYLOAD	PAYLOAD ORGANZATION	DATE	PAGE
G-0321	*Air Force Institute of Technology*	*mm/dd/yy*	*1*

SUBSYSTEM	HAZARD CATEGORY							
	Collision	Contamination	Corrosion	Electrical Shock	Explosion	Fire	Temperature Extremes	Radiation
Inflation								
Rigidization								
Excitation								
Electrical				X				
Environmental Heaters								
Pressure Systems					X			
Materials								
Mechanical								
Structure								

FIGURE 3.4.2-1 - GROUND OPERATIONS

GAS HAZARD DESCRIPTION – FLIGHT OPERATIONS		
PAYLOAD NUMBER & ORGANIZATION G-0321 *Air Force Institute of Technology*	SUBSYSTEM (Ex: Electrical)	DATE mm/dd/yy

HAZARD GROUP	BRIEF DESCRIPTION OF HAZARD	APPLICABLE SAFETY REQUIREMENTS
Inflation	During Inflation, the tubes will extend outward from their storage containers. The tubes will have insufficient force to breech the GAS canister	
Electrical	The battery system and power wiring will follow NASA standards and regulations.	
Enviromental Heaters	The heaters used in the rigidization process will operate at approximately 150 C. The heating structure will be isolated to minimize heat transfer to the structure and the heaters will only operate for a short duration.	
Pressure System	The inflation cylinders will contain pressurized nitrogren. The cylinders are rated at 1800 psia, which is 300% greater than required. Any leaks in the pressure system will vent through the filtered relief valve.	
Structure	Failure of the structural frame. Any structural failure will be contained within the GAS canister.	

FIGURE 3.4.2-2 FLIGHT OPERATIONS

GAS HAZARD DESCRIPTION – GROUND OPERATIONS		
PAYLOAD NUMBER & ORGANIZATION **G-0321** ***Air Force Institute of Technology***	**SUBSYSTEM** **(Ex: Electrical)**	**DATE** **mm/dd/yy**

HAZARD GROUP	BRIEF DESCRIPTION OF HAZARD	APPLICABLE SAFETY REQUIREMENTS
Electrical	**The battery system will be installed in the experiment during integration. The battery system and power wiring will follow NASA standards and regulations.**	
Pressure System	**The inflation cylinders will be charged to approximately 250 psia during integration. The cylinders are rated at 1800 psia, which is 300% greater than required.**	

FIGURE 3.4.2-2 GROUND OPERATIONS

3.5 Post Flight Shuttle Mission Data

GSFC will provide the customer with two types of data concerning the Shuttle mission on which this payload has flown:

- **a. Mission Elapsed Time (MET) for major attitude holds; with an indication when the Orbiter was pointing at the Earth, Deep Space, or the Sun.**
- **b. Approximate time (±1min.) of GCD relay operations during the mission.**

4.0 OPTIONAL SERVICES

All optional services provided by NASA will be at additional cost as negotiated between NASA and the Customer. The optional services charge for G-0321will be $0.00.

4.1 Additional Post-Flight Mission Data	*None*
4.2 Optical Window (10 lb. weight penalty)	*None*
4.3 Standard Door Assembly (SDA) (40 lb. weight penalty)	*None*
4.4 Special Launch Site Support Requirements	*None*

5.0 TECHNICAL SUPPORT SERVICES

Technical support services required by GAS users and provided by the GSFC (such as vibration testing, EMI testing, etc.) are provided at extra cost. Costs for these services are negotiated between the GSFC GAS project and the customer and are funded directly to the GSFC as a reimbursable effort.

5.1 The following items fit this category:

None at this time.

6.0 SCHEDULE

The earliest acceptable launch date for the G-0321 payload is 1 Apr 02.

It is understood that the GSFC is required to submit safety data, in accordance with NSTS 1700.7B and JSC 13830, to the Johnson Space Center's Payload Safety Review Panel *no later than* 60 days prior to delivery of a user's payload at the Kennedy Space Center. With the understanding that payload integration occurs nominally 2-3 months prior to a specific launch date, the following schedule represents the expected safety data submittals for the G-0321 payload:

		EXPECTED COMPLETION DATE *(Fill in dates for your payload)*	DATE RECEIVED AT GAS PROJECT OFFICE (OFFICAL USE ONLY)
DOCUMENT	**Preliminary Safety Data Package (PSDP)**		
	Final Safety Data Package (FSDP)		
	Materials List		
	Structural Analysis		
	Thermal Analysis		
	Energy Containment Analysis		
	Phase III Safety Data Package		
	Reflight Safety Data Package	**Payload: G-0321** **Date Submitted: __________**	

TABLE 6.0-1
MILESTONE SCHEDULE FOR GET AWAY SPECIAL PAYLOAD G-0321

THIS SCHEDULE IS FOR PLANNING PURPOSES ONLY. IT IS NOT AN OFFICIAL FLIGHT ASSIGNMENT.

Appendix B. Inflation Gas Calculations

Using the Ideal Gas Law (pV=nRT), the minimum amount of nitrogen gas required to ensure adequate pressure throughout the inflation and rigidization process is calculated. Additionally, the cylinder pressure at several temperatures is calculated to ensure the pressure does not exceed the cylinder specifications.

ASSUMPTIONS:

- Tube dimension are 1.375 in diameter by 22 inch length (overall length)
- Nitrogen cylinder has volume of 50 cm^3
- Minimum temperature of environment is -160^o C
- Maximum temperature of oven/tube is +150^o C
- Multiply final values by 125% factor of safety

$$pV = nRT; \qquad R = 73.628 \frac{lb \cdot in}{mol \cdot K} \tag{B.1}$$

$$V_{tube} = \pi R^2 L \qquad V_{tube} = 32.67\, in^3 \tag{B.2}$$

Inside Tube:

$$p_{tube} = 4psia\, (\frac{lb}{in^2}) \tag{B.3}$$

$$n_{at\,T} = \frac{p_{tube} V_{tube}}{RT} \tag{B.4}$$

$$at\, T = -160^oC = 113K; \qquad n_{(-160)} = 0.01571\, mol \tag{B.5}$$

$$at\, T = 150^oC = 423K; \qquad n_{(150)} = 0.00419\, mol \tag{B.6}$$

$$n_{required} = 1.25 \cdot (n_{(-160)} + (n_{(-160)} - n_{(150)}) \qquad n_{required} = 0.03403\, mol \tag{B.7}$$

Inside Cylinder:

$$V_{cyl} = 50cm^3 = 3.058in^3 \tag{B.8}$$

$$p_{at\,T} = \frac{nRT}{V_{cyl}} \tag{B.9}$$

$$at\,T = -160^oC = 113K; \qquad p_{(-160)} = 92.58\,psia \tag{B.10}$$

$$at\,T = 0^oC = 273K; \qquad p_{(0)} = 223.65\,psia \tag{B.11}$$

$$at\,T = 32^oC = 305K; \qquad p_{(32)} = 249.86\,psia \tag{B.12}$$

$$at\,T = 100^oC = 373K; \qquad p_{(100)} = 305.61\,psia \tag{B.13}$$

$$at\,T = 150^oC = 423K; \qquad p_{(150)} = 346.58\,psia \tag{B.14}$$

Therefore, the minimum amount of nitrogen gas required is 0.03403 moles. Assuming the cylinder is charged at room temperature (32^o C), it should be charged to a pressure of 250 psia. The highest possible temperature experienced by the cylinder is the maximum temperature of the oven (150^o C). At the maximum temperature, the cylinder used must be able to withstand a pressure of 347 psia.

Appendix C. Data Storage Analysis

To calculate the approximate amount of data storage required for the duration of the experiment, the data was broken up into four categories: environmental, inflation and rigidization, modal analysis, and video. In order to perform the calculations, several assumptions were made with regard to unknown values.

C.1 Environmental Data

Assumptions:

- Scan all sensors at 1 Hz.
- Total experiment active time is 240 minutes.

$$n_{sensors} = 1\,pressure + 1\,voltage + 4\,temperature = 6\,sensors \tag{C.1}$$

$$D_{enviro} = 1\frac{points}{sec} \cdot \frac{60sec}{min} = 60\frac{points}{sec} \tag{C.2}$$

$$D_{enviro} = 60\frac{points}{sec} \cdot \frac{16\,bits}{point} \cdot \frac{byte}{8\,bits} = 120\frac{bytes}{sec} \tag{C.3}$$

$$D_{enviro} = 120\frac{bytes}{min} \cdot 240\,min = 28800\,bytes \approx 0.03\,Mb \tag{C.4}$$

C.2 Inflation and Rigidization Data

Assumptions:

- Sample each sensor at 1 Hz.
- Structure warming time is 15 minutes.
- Inflation time is 1 minute
- Rigidization time is 15 minutes.

$$n_{channels} = 3\,temperature + 1\,pressure = 4 \tag{C.5}$$

$$t_{inf} = 15\,min\ + 1\,min = 960\,sec \tag{C.6}$$

$$t_{rig} = 15\,min = 900\,sec \tag{C.7}$$

$$D_{inf} = n_{channels} \cdot \frac{1\,point}{second} \cdot t_{inf} = 3840\,points \tag{C.8}$$

$$D_{rig} = n_{channels} \cdot \frac{1\,point}{second} \cdot t_{rig} = 3600\,points \tag{C.9}$$

$$D_{per\ tube} = D_{inf} + D_{rig} = 7440\,points \tag{C.10}$$

$$D_{per\ tube} = 7440\,points \cdot \frac{16\,bits}{point} \cdot \frac{byte}{8\,bits} = 14880\,\frac{bytes}{tube} \tag{C.11}$$

$$D_{inf\&rig} = 14880\,\frac{bytes}{tube} \cdot 3\,tubes = 44640\,bytes \approx 0.05Mb \tag{C.12}$$

C.3 Modal Analysis Data

Assumptions:

- Sample each sensor at 1 kHz.
- 4 seconds of data is 1 block.
- Require 9 blocks per cycle with 50 percent overlap.
- Two axis excitation with 10 sets of excitations is 20 cycles per tube.

$$n_{channels} = 1\, force + 3\, tube\ accelerometer$$
$$+ 3\, environmental\ accelerometer = 7 \tag{C.13}$$
$$n_{blocks} = blocks\ of\ data\ @\ 50\%\ overlap \tag{C.14}$$
$$t_{cycle} = \frac{4sec}{block} \cdot \frac{n_{blocks}+1}{2} = 20sec \tag{C.15}$$
$$D_{block} = 1024\frac{points}{sec \cdot channel} \cdot \frac{4sec}{block} = 4096\frac{points}{block \cdot channel} \tag{C.16}$$
$$D_{cycle} = D_{block} \cdot \frac{n_{blocks}+1}{2} blocks = 20480\frac{points}{cycle \cdot channel} \tag{C.17}$$
$$D_{analysis} = D_{cycle} \cdot \frac{7\, channels}{tube} = 143360\frac{points}{tube \cdot cycle} \tag{C.18}$$
$$D_{analysis} = 143360\frac{points}{tube \cdot cycle} \cdot \frac{16\, bits}{point} \cdot \frac{byte}{8\, bits} \approx 0.28\frac{Mb}{tube \cdot cycle} \tag{C.19}$$
$$D_{analysis} \approx 0.28\frac{Mb}{tube \cdot cycle} \cdot 3\, tubes \cdot 20\, cycles \approx 16.8Mb \tag{C.20}$$

C.4 Video Data

Assumptions:

- Image size of 1000 by 1000 pixels.
- Image grey scale of 256 shades.

$$n_{images} = 6\, during\ inflation + 2\, after\ inflation$$
$$+ 2\, after\ rigidization + 2\, after\ venting = 12 \tag{C.21}$$
$$x = \#\, of\ pixels = 1000 \cdot 1000 = 10^6\, pixels \tag{C.22}$$
$$b = \#\, of\ bits\ per\ pixel;\ 256 = 2^8\ \Rightarrow b = 8\frac{bits}{pixel} \tag{C.23}$$
$$D_{video} = 10^6\, pixels \cdot 8\frac{bits}{pixel} \cdot \frac{1\, byte}{8\, bits} = 10^6\, bytes \tag{C.24}$$
$$D_{video} \approx 1\, Mb\, per\ image \cdot 3\, tubes \cdot \frac{12\, images}{tube} \approx 36\, Mb \tag{C.25}$$

C.5 Data Totals

Using the data from each category, the total results are summarized below.

Table C.1 Data Storage Requirements

Sensors	Data Rate	Quantity	Factor	Total
Environmental	$\frac{\text{120 bytes}}{\text{minute}}$	1	240 minutes	0.03 Mb
Inflation Rigidization	$\frac{\text{14880 bytes}}{\text{tube} \cdot \text{cycle}}$	3 tubes	1 cycle	0.05 Mb
Modal Analysis	$\frac{\text{0.28 Mb}}{\text{tube} \cdot \text{cycle}}$	3 tubes	20 cycles	16.8 Mb
Video	$\frac{\text{1 Mb}}{\text{tube} \cdot \text{image}}$	3 tubes	12 images	36 Mb
			Grand Total	**52.88**

Appendix D. Weight and Cost Analysis

To calculate the preliminary weight and hardware cost of the experiment, grass-roots estimating was used. In grass-roots estimating, the system is broken down into the lowest level components. The cost and weight of each component is then determined by various methods. After all components values are known, the total cost and weight of the system can be determined by adding up the individual values.

To determine the cost and weight of each component, several techniques were used. The most accurate data was available for commercial products. Although specific suppliers have not been selected, the cost and weight data for a typical component was used for this analysis.

For components that must be custom made, calculations and estimates were used to determine the cost and weight. For example, the weight of the structure was calculated by determining the volume of aluminum required, length times width times depth. The volume was then multiplied by the density of aluminum to calculate the weight. However, this is only an estimate since the density of aluminum varies with the type of aluminum selected. For safety, the following relatively high densities were selected for aluminum (Al) and thermoplastic (Plas):

- $\rho_{Al} = 175 \frac{pounds}{ft^3}$
- $\rho_{Plas} = 100 \frac{pounds}{ft^3}$

To calculate the cost of the material, a similar method was used. The area of material required was calculated, length times width, and then the sheet cost for the material thickness was used to determine cost. The following cost values were used:

- $Cost_{0.25\ in\ Al} = 25 \frac{dollars}{ft^2}$
- $Cost_{0.50\ in\ Al} = 50 \frac{dollars}{ft^2}$
- $Cost_{0.25\ in\ Plas} = 100 \frac{dollars}{ft^2}$

If accurate manufacturer data was not available and calculations were not available, the cost and weight of the component were estimated. Estimations were based on available data and expert opinion. In all cases, worst case estimates were used to minimize the amount of increase in the final design.

The component data for weight and cost are summarized in Tables D.1 and D.2. The data is then separated and presented for each assembly in the weight and cost analysis sections of Chapter 4.

Table D.1 Weight and Cost Analysis Data

Assembly Component	Weight (lbs)	Cost ($)	Method	Quantity
Structure	**58.24**	**675**		
Top	7.76	100	C	1
Bottom	15.51	200	C	1
Base	1.54	25	C	1
Bumpers	0.61	25	C	4
Walls	30.99	250	C	1
Battery Cell	**6.60**	**25**		
Battery	0.33	1.25	D	20
Battery Box	**18.6**	**350**		
Structure	17.60	150	C	1
Fittings/Tubing	1.00	200	E	1
Computer	**7.75**	**2650**		
CPU	0.50	500	D	1
Cards	0.25	350	E	5
Memory	(CPU)	500	D	1
Container	6	100	D	1

Table D.2 Weight and Cost Analysis Data (Cont.)

Assembly Component	Weight (lbs)	Cost ($)	Method	Quantity
Sensors	**2.48**	**7650**		
Accelerometer (Exp)	0.10	1000	D	3
Accelerometer (Env)	0.13	1300	D	1
Temperature	0.10	150	E	5
Pressure	0.25	250	E	4
Voltage	0.10	100	E	1
Force	0.10	500	E	3
Environmental Heaters	**1**	**150**		
Heater	0.25	100	D	1
Controller	0.75	150	D	1
Oven	**4.25**	**700**		
Structure	3.00	100	C	1
Heaters	0.25	500	E	1
Springs/Pins	2.00	100	E	1
Inflatables	**2.50**	**600**		
Tubes	1.00	500	E	1
Flanges	0.75	50	E	2
Inflation System	**5.25**	**785**		
Cylinder	0.50	60	D	1
Relief Valve	0.25	75	E	1
Solenoid	1.50	200	E	1
Pressure Reducer	1.50	200	E	1
Fittings/Tubing	1.50	250	E	1
Video	**0.75**	**1650**		
Camera	0.50	1550	D	1
Light	0.25	100	E	1
Test Equipment	**0**	**8450**		
Heaters	-	500	E	1
Laser Displacement	-	5000	E	1
Ground Computer	-	2000	E	1
PC/104 Dev. Kit	-	950	E	1

Appendix E. Drawings

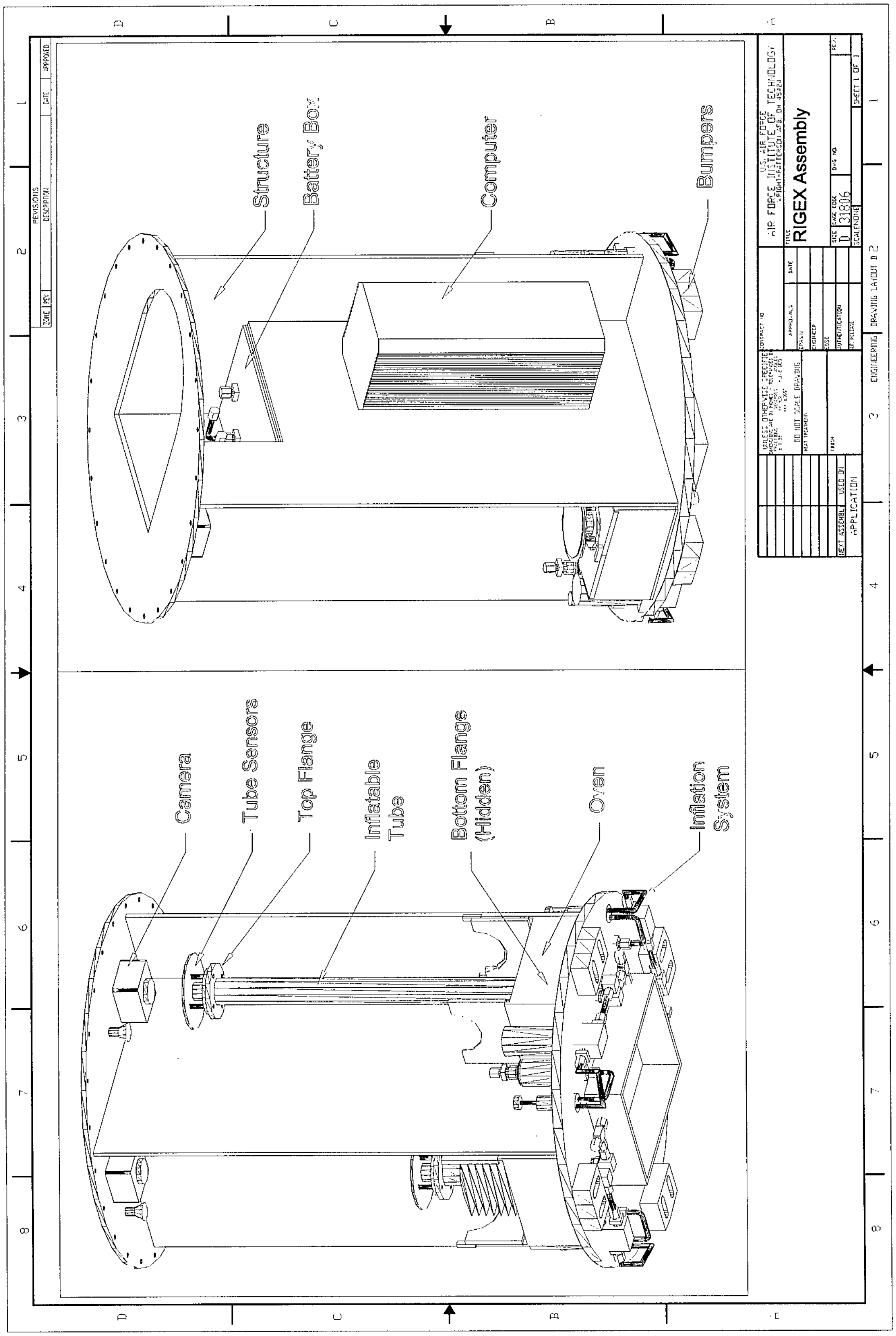
In addition to the commercial components, several parts must be custom built for the design. These parts include the structure, battery box, ovens, and flanges for the inflatable tubes. As with much of the design, the final configuration of these components is driven by the integration into the complete design. The preliminary design of each part, along with detailed dimensions are included as a starting point.

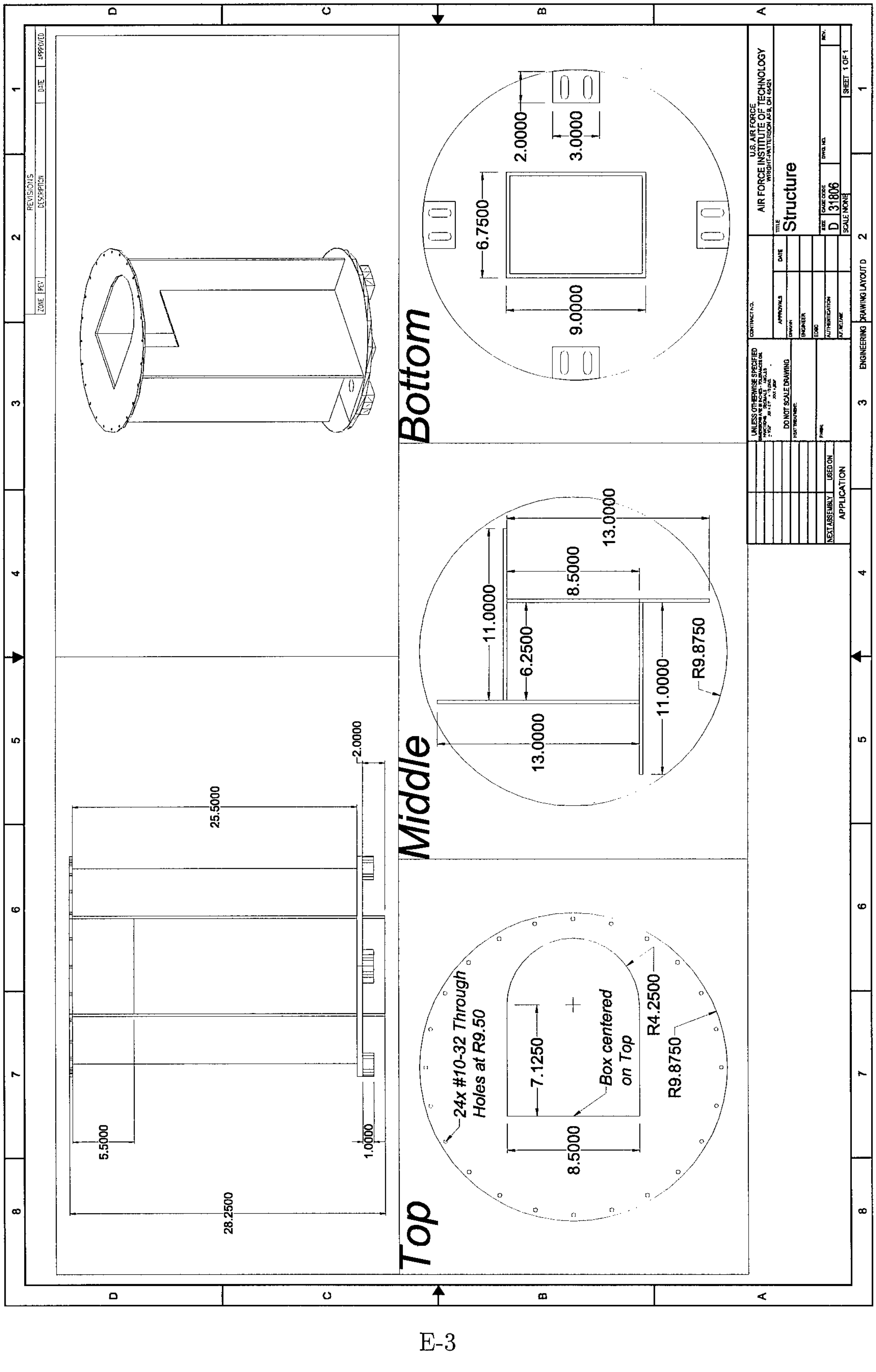
The first drawing displays the configuration of the preliminary design. The structure is made of one-quarter inch aluminum plates (except for the bottom plate which is one-half inch aluminum) and welded at the joints. The top plate of the structure has twenty-four holes for securing to the EMP provided by NASA.

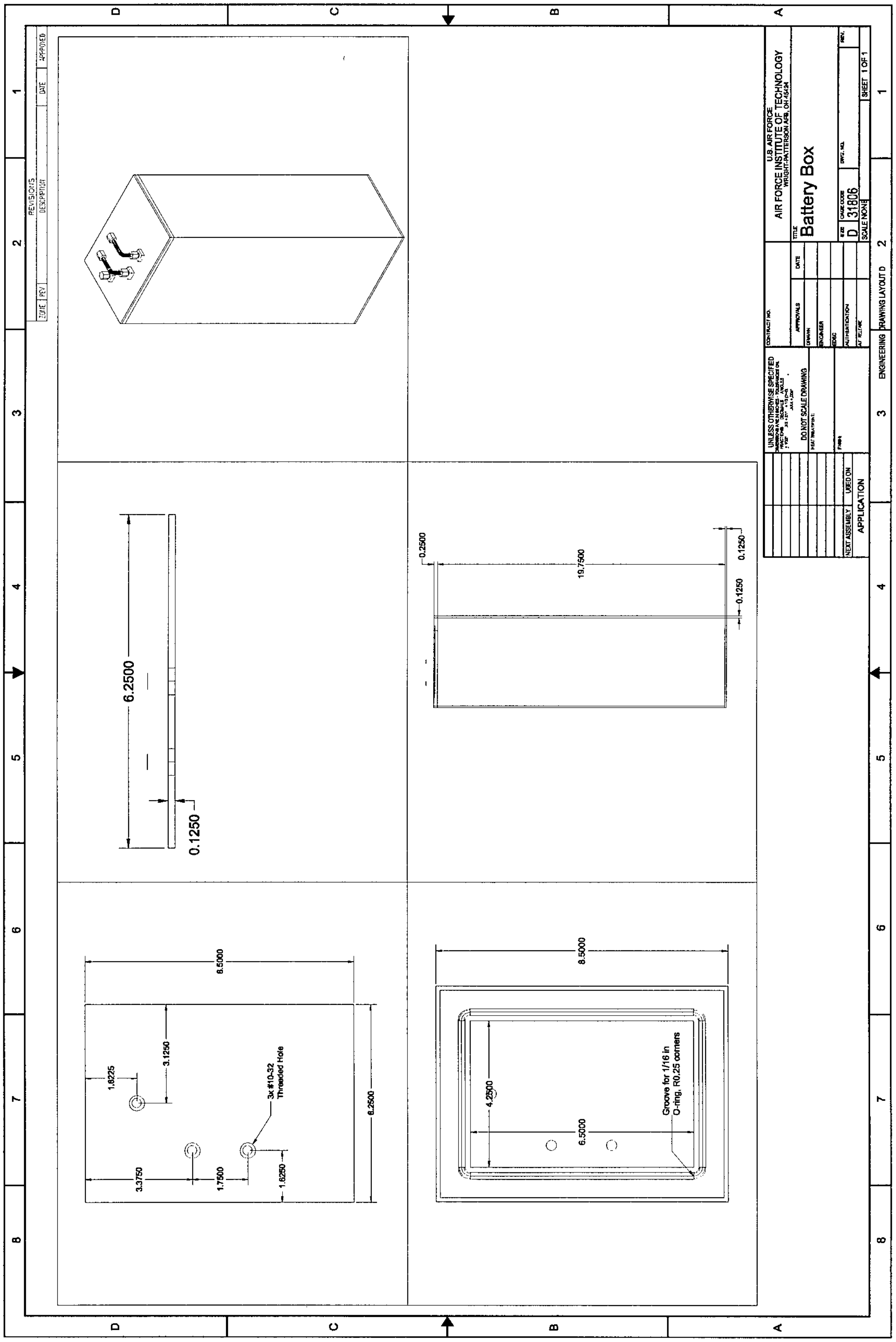
The battery box is constructed of one-eighth inch aluminum plates and welded at the joints. The cover of the battery box is one-quarter inch aluminum and connects to the top of the box with #10-32 socket head cap screws.

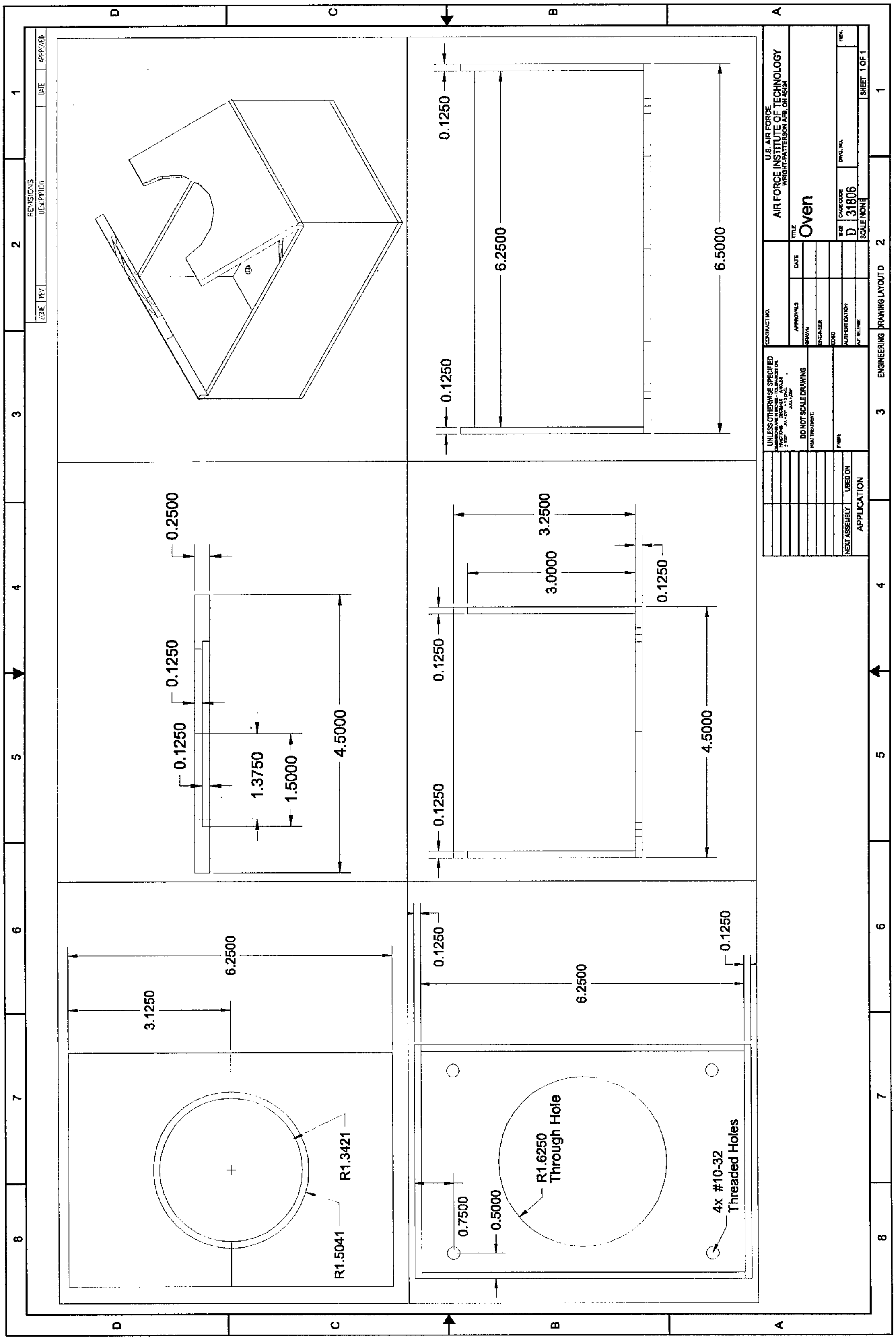
The oven is constructed of one-eighth inch low-conductance thermoplastics to minimize heat transfer out of the oven. The top of the oven is hinged at the ends and grooved to hold the top flange when closed. Commercial pins are used to hold the oven closed until inflation.

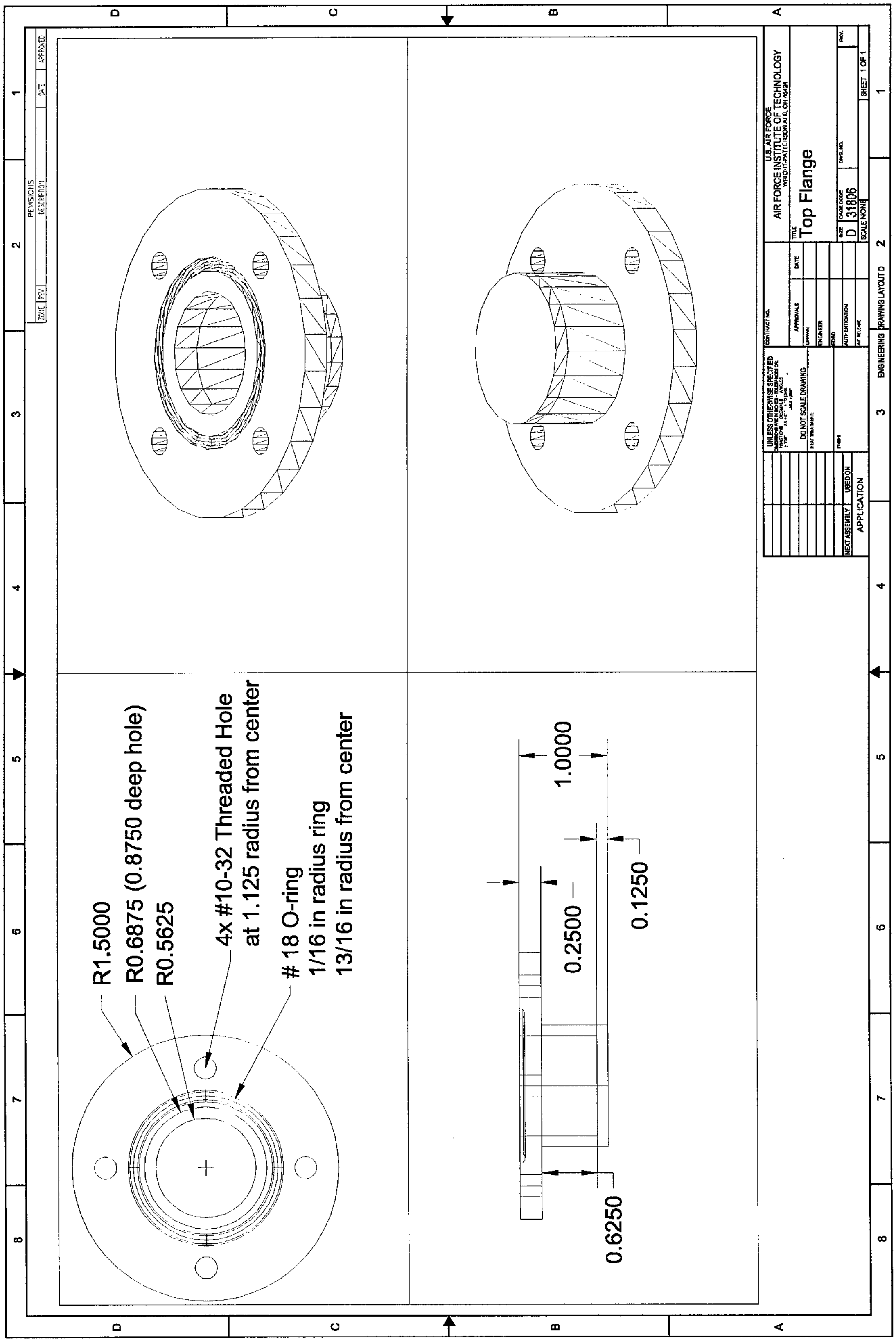
The flanges are also constructed of low-conductance thermoplastics. The inflatable structure is slid over the flange and connected with an adhesive. The top flange is capped to create an airtight seal and allow a cavity for mounting sensors. The bottom flange has a groove for an o-ring and is hollow to allow the inflation system access to the tubes. Both flanges have #10-32 threaded holes for mounting the bottom to the structure and the top to the sensors.

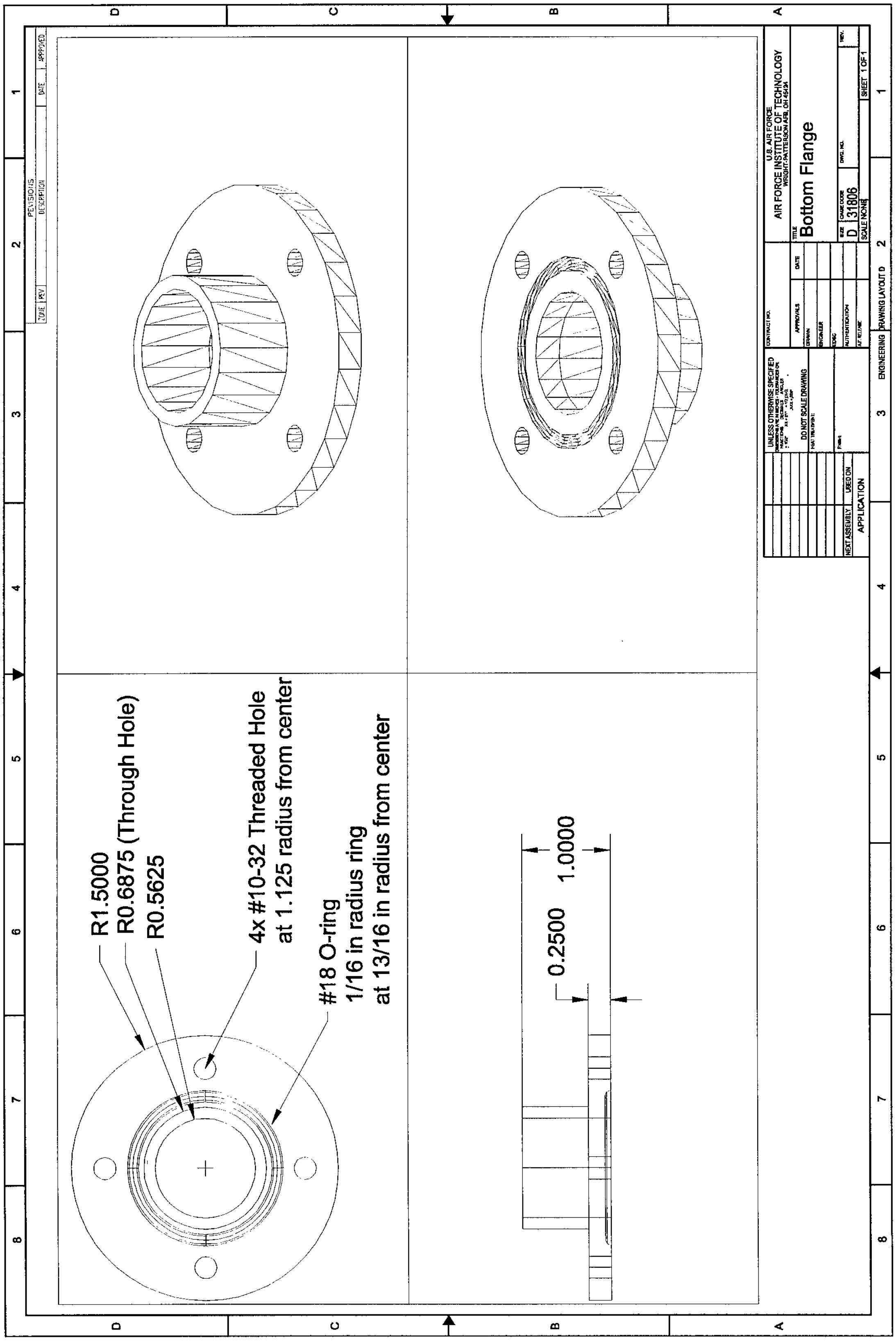

Camera
Tube Sensors
Top Flange
Inflatable Tube
Bottom Flange (Hidden)
Oven
Inflation System
Structure
Battery Box
Computer
Bumpers
U.S. AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
RIGEX Assembly
D
31806
DO NOT SCALE DRAWING
ENGINEERING DRAWING LAYOUT D 2
NEXT ASSEMBLY
USED ON
APPLICATION


Top
Middle
Bottom
24x #10-32 Through Holes at R9.50
Box centered on Top
R4.2500
R9.8750
7.1250
8.5000
28.2500
25.5000
5.5000
1.0000
2.0000
13.0000
11.0000
6.2500
9.0000
6.7500
3.0000
REVISIONS
U.S. AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AFB, OH 45433
Structure
D
31806
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED
DO NOT SCALE DRAWING
NEXT ASSEMBLY
USED ON
APPLICATION
ENGINEERING DRAWING LAYOUT D


U.S. AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
Battery Box
D
31806
SCALE NONE
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED
DO NOT SCALE DRAWING
NEXT ASSEMBLY
USED ON
APPLICATION
ENGINEERING DRAWING LAYOUT D
REVISIONS
6.2500
0.1250
0.2500
19.7500
0.1250
0.1250
8.5000
6.2500
1.8225
3.1250
3.3750
1.7500
1.6250
3x #10-32 Threaded Hole
8.5000
4.2500
6.5000
Groove for 1/16 in O-ring, R0.25 corners


REVISIONS
DESCRIPTION
DATE
APPROVED
0.1250
6.2500
6.5000
0.2500
0.1250
0.1250
1.3750
1.5000
4.5000
3.2500
3.0000
0.1250
0.1250
0.1250
4.5000
3.1250
6.2500
R1.3421
R1.5041
0.1250
6.2500
0.1250
0.7500
0.5000
R1.6250
Through Hole
4x #10-32
Threaded Holes
UNLESS OTHERWISE SPECIFIED
DO NOT SCALE DRAWING
NEXT ASSEMBLY
USED ON
APPLICATION
CONTRACT NO.
APPROVALS
DATE
DRAWN
U.S. AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AFB, OH 45433
TITLE
Oven
SIZE
CAGE CODE
D
31806
DWG. NO.
REV.
SCALE NONE
SHEET 1 OF 1
ENGINEERING DRAWING LAYOUT D


R1.5000
R0.6875 (0.8750 deep hole)
R0.5625
4x #10-32 Threaded Hole
at 1.125 radius from center
18 O-ring
1/16 in radius ring
13/16 in radius from center
1.0000
0.2500
0.1250
0.6250
REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
UNLESS OTHERWISE SPECIFIED
DO NOT SCALE DRAWING
NEXT ASSEMBLY
USED ON
APPLICATION
CONTRACT NO.
APPROVALS
DATE
DRAWN
ENGINEER
U.S. AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
TITLE
Top Flange
SIZE
CAGE CODE
DWG. NO.
REV.
D
31806
SCALE NONE
SHEET 1 OF 1
ENGINEERING DRAWING LAYOUT D


R1.5000
R0.6875 (Through Hole)
R0.5625
4x #10-32 Threaded Hole
at 1.125 radius from center
#18 O-ring
1/16 in radius ring
at 13/16 in radius from center
0.2500
1.0000
U.S. AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AFB, OH 45434
Bottom Flange
D 31806
SCALE NONE
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED
DO NOT SCALE DRAWING
NEXT ASSEMBLY
USED ON
APPLICATION
ENGINEERING DRAWING LAYOUT D
REVISIONS

Vita

Captain John D. DiSebastian graduated from Venice High School in Venice, Florida in June 1992. He entered undergraduate studies at Embry-Riddle Aeronautical University in Daytona Beach, Florida where he graduated with a Bachelor of Science Degree in Engineering Physics in December 1996.

His first assignment was as a developmental engineer at Technical Operations Division, McClellan AFB, California. While assigned there he held several positions, including Nuclear Plant Program Engineer, Project Officer for Field Systems, and Chief of Unit Closure and Transition. In August 1999, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the Air Force Operational Test and Evaluation Center at Kirtland AFB, New Mexico.

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14. ABSTRACT
As space structures grow in size and complexity, their weight and cost increase considerably. The use of inflatable and rigidizable structures offers drastic improvements in all areas of spacecraft design. The goal of this experiment is to verify and validate ground testing of inflation and rigidization methods for inflatable space structures. The Rigidized Inflatable Get-Away-Special Experiment is an autonomous, self-contained space shuttle experiment that will inflate and rigidize several structures. After inflation, the experiment will perform a structural analysis by exciting the rigidized structures and collecting vibration data. A systems engineering approach is utilized to make design decisions based on a total system and life-cycle perspective.

15. SUBJECT TERMS
Inflatable, Rigidized, Get Away Special, GAS, Design, RIGEX, Systems Engineering

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